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The case against specialized visual-spatial short-term memory

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Abstract

The dominant paradigm for understanding working memory, or the combination of the perceptual, attentional, and mnemonic processes needed for thinking, sub-divides short-term memory according to whether memoranda are encoded in aural-verbal or visual formats. This traditional dissociation has been supported by examples of neuropsychological patients who seem to selectively lack short-term memory for either aural-verbal, visual, or spatial memoranda, and by experimental research using dual-task methods. Though this evidence is the foundation of assumptions of modular short-term memory systems, the case it makes for a specialized visual short-term memory system is surprisingly weak. I identify the key evidence supporting a distinct verbal short-term memory system—patients with apparent selective damage to verbal short-term memory and the resilience of verbal short-term memories to general dual-task interference—and apply these benchmarks to neuropsychological and experimental investigations of visual-spatial short-term memory. Contrary to the evidence on verbal short-term memory, patients with apparent visual or spatial short-term memory deficits tend to experience a wide range of additional deficits, making it difficult to conclude that a distinct short-term store was damaged. Consistently with this, a meta-analysis of dual-task visual-spatial short-term memory research shows that robust dual-task costs are consistently observed regardless of the domain or sensory code of the secondary task. Together, this evidence suggests that positing a specialised visual short-term memory system is not necessary.

Keywords: working memory, short-term memory, visual memory, spatial memory, interference, neuropsychology, meta-analysis

Public Significance Statement

This study challenges the popular notion that there is a distinct short-term visual memory system in which recent visual memories are maintained separately from other sorts of memories. It is important to understand how normal memory functions and how it interacts with other cognitive, perceptual, and motor systems to advise those who want to make the most of their memories. This work shows that visual memories are vulnerable to interference from a variety of sources.

The case against specialized visual-spatial short-term memory

The most prominent model of working memory, the multi-component model of working memory (Baddeley, 2012), posits that visual and verbal information are stored separately from each other in dedicated storage buffers. This model, one of the most influential theoretical frameworks in cognitive psychology, arose to explain two key findings: 1) neuropsychological case evidence suggesting that it could be possible to selectively lose access to aural-verbal or visual or spatial short-term memories, and 2) observations of little or no interference between serial recall of verbal lists and concurrent non-verbal tasks (Baddeley & Hitch, 1974). Together these pieces of evidence suggested that a comprehensive memory system must include some system for short-term storage, and furthermore that verbal short-term storage must be distinguished from other mnemonic processes.

By logical inference, a comparable short-term memory system specialized for visual information has likewise been included in some models of working memory (Baddeley, 1986; Baddeley, 2000; Baddeley, 2012; Baddeley & Logie, 1999; Logie, 2011; Repovš & Baddeley, 2006). Analogously to the proposed verbal short-term memory system, which includes sub-components for storing phonological information and for articulatory rehearsal (Baddeley, 2012), the visual short-term memory system includes sub-components for maintaining and rehearsing visual materials (Logie, 2011). However, direct evidence supporting an exclusively visual-spatial short-term memory system that functions similarly to a verbal short-term memory system is actually quite weak. For many years, the study of visual memory lagged behind that of verbal memory, and during this period it was perhaps reasonable to rely on assumptions of similarity between verbal and visual-spatial short-term memory systems to generate theoretical predictions. However, sufficient evidence about visual short-term memory from a variety of sources has now accumulated, and this evidence should be used to reconsider theoretical assumptions about visual short-term memory.

I argue that the proposition of a dedicated short-term store for visual materials is not essential for explaining *any* of the evidence from the memory literature, including neuropsychological cases that purport to demonstrate selective visual or spatial short-term memory deficits. I show that the evidence called upon to support the idea of a visual short-term memory buffer never unequivocally led to this conclusion, but exploratory study of visual-spatial short-term memory was nonetheless guided by assumptions that memory for and operations performed on visual information would be analogous to those posited for verbal memory. After decades of accumulated research, evidence for parallels between visual-spatial and verbal short-term memory systems has consistently proved weak and inconclusive. Despite these weaknesses, disconfirming evidence that weighs against the notion of a distinct visual short-term memory system has been disregarded, to the detriment of useful advances in working memory theory. I aim to demonstrate that there is now sufficient evidence available to reject the notion of a dedicated visual-spatial short-term memory store, and to persuade researchers to consider various alternative formulations for explaining domain-specific dissociations in memory.

Describing a hypothetical visual short-term memory system

The visual-spatial short-term memory system in Baddeley's multi-component model, termed the *visuo-spatial sketchpad*, has often been apologetically introduced to readers. Descriptions of the visuo-spatial sketchpad frequently begin by acknowledging that, in contrast to the verbal memory system (including the *phonological store* for holding verbal information and the *articulatory loop* for rehearsing it in serial order), little research supports a comprehensive description of the visuo-spatial short-term memory component (e.g., Gathercole, 1994; Repovš and Baddeley, 2006). Despite the accumulation of evidence pertaining to visual memory, contemporary accounts of the multi-component model still describe the visual portions of it using the same cautious and exploratory language used 20-30 years ago. Baddeley (2012) limits his description of the visuo-spatial sketchpad mainly to the supposition of fractionation into sub-components for handling spatial versus visual imagery, much as Gathercole (1994) previously did. As for components meant for carrying out rehearsal, evidence about these is still deemed "unclear" (Baddeley, 2012).

Yet a visual short-term memory system *was* proposed, and is still widely considered an essential component of a working memory system. What evidence led to the belief that a specialized visual-spatial short-term memory system must exist, even before it could be described with any empirically-derived concrete detail? Baddeley's admitted philosophy of scientific practice is for theory to follow from data, rather than for theory to predict experimental outcomes (Baddeley, 1992; 2012). However, in the instance of the visuo-spatial sketchpad, it is difficult to re-trace how data led to the supposition of a visual short-term memory system rather than to other possibilities that are equally consistent with the same empirical outcomes. Rather, it seems that some component was required to explain retention of non-verbal information, and a visual-spatial short-term memory system was chosen to complement the verbal one based on logical deduction, not because of data that could not be explained in any other manner. At this early stage, the proposition of a visual-spatial short-term memory system was the logical complement to the better-established verbal one, and was assumed on the strength of evidence about the independence of verbal memory from other cognitive processes.

The assumption of distinct, specialized verbal and visual-spatial short-term memory systems has consistently guided exploration of memory phenomena, and arguably still does.

Contemporary hypothesis testing about visual short-term memory continues to rely heavily on analogy with verbal short-term memory, explicitly applying principles rooted in the study of verbal short-term memory to non-verbal memory tasks, and evaluating whether the analogy holds (e.g., Allen, Baddeley, & Hitch, 2014; Jünger, Kliegl, & Oberauer, 2014). It would therefore seem that, rather than theory about visual short-term memory following from data, theory about visual short-term memory follows from theory about verbal short-term memory, plus assumptions that similar verbal and visual sub-systems must co-exist. While work probing similarities and differences between verbal and non-verbal memory is important for better establishing boundary conditions on memory phenomena, such work does not actually address whether distinct but similar verbal and visual-spatial systems underlie performance. Assuming separate sub-systems might misguide our interpretation of data, which is perhaps why descriptions of visual-spatial working memory remain speculative despite years of accumulated research. It is time that we reconsidered the available evidence and abandon the assumption that a specialized visual short-term memory system exists, at least temporarily.

Reconsideration of evidence

To understand the progress made in describing how we retain visual memoranda and how this process differs from retaining verbal memoranda, I first review the empirical evidence that led to the supposition of a visual short-term memory system, updating this with recent reports of evidence from the same kinds of tasks. These tasks investigated whether the use of visual imagery augmented verbal memory, and classic dual-task interference manipulations were applied in order to test for selective disruption of the use of these visual imagery mnemonics. While evidence from these manipulations does strongly suggest that the same information may be retained in verbal or visual format, it is vital to note that this does not necessarily mean that these representations are held in distinct short-term memory systems.

Evidence from neuropsychological cases has been proposed as the smoking-gun justification of separate verbal and visual-spatial short-term memory systems. A handful of individuals with apparently selective deficits exclusive to either auditory-verbal or visual-spatial short-term memory have been reported, and their performance on a variety of tasks has been documented. The existence of an individual who could not remember visual information over brief retention intervals, but whose long-term memory and cognitive functioning were otherwise unaffected, would provide formidable evidence supporting a specialized visual-spatial short-term memory system. I describe the patients with visual or spatial short-term memory deficits, attempting to examine the evidence they provide without the a priori assumption of a specialized visual short-term memory system. Though patients with some degree of difficulty with visual and/or spatial short-term memory have been reported, I argue that most of these patients do not show the focused pattern of selective deficits required to support the proposition of a specialized visual-spatial short-term memory system. Additionally, I highlight methodological discrepancies in the case evidence that preclude coming to an unambiguous interpretation, which include inconsistent measures across patients, and differences in the tasks used to measure verbal, spatial, and visual memory that extend beyond the sensory code of the to-be-remembered content.

Because in my view the evidence that informed the multi-component model of working memory was always ambiguous and capable of supporting multiple proposals of how visual information is mentally represented, I outline a set of hypothesis tests that would confirm the presumption of a specialized visual-spatial short-term memory system. I then evaluate these hypotheses via a re-examination of a previously-published data set and via a comprehensive meta-analysis of classic and contemporary studies including experimental dual-task manipulations during visual short-term memory tasks. In summary, I find no reason to believe that visual or spatial memories are retained by a distinct, specialized short-term memory system. I propose that rather than using assumptions about verbal short-term memory as the guiding principle for understanding visual memory, we accept the inherent asymmetry between representing verbal and non-verbal memoranda and systematically compare possible reasons for it.

Experimental evidence informing the early multi-component working memory model

Visual imagery mnemonics applied to verbal memory

The early work that led to confirmation that a specialized visual module comparable to the verbal working memory system must be operating incorporated several lines of experimental evidence, but oddly, very little of it required participants to explicitly remember visual images or spatial sequences. Much of the work cited as inspiring the concept of the visuo-spatial sketchpad investigated how visualization may be enlisted to enhance memory for verbal information. Though this evidence has been taken as support for a specifically visual short-term memory system, I argue that interpretation of this evidence does not actually require this assumption. First, I review this body of research and then I consider what limitations it reasonably places on working memory theory.

Brooks' tasks. Brooks (1967) devised a task for investigating whether visual-spatial mnemonic processes could assist verbal memory. Several to-be-remembered sentences are presented with respect to an imaginary grid. For example, a sequence may begin "place 1 in the central square", and continue with "place 2 in the square to the right", "place 3 in the square above", etc., changing whether the direction word is *above, below, left,* or *right*. With this formulation, imagining the numbers entered onto a spatial layout aids sentence recall. Verbal recall in this spatial path condition is contrasted with verbal recall in a nonsensical version in which the directional words are replaced with another set of adjectives that lack any spatial mapping (e.g., “place 2 in the square to the good”, “place 3 in the square to the quick”, etc.). In both versions, the participant's object is to try to recall the sentences in their presented serial order. Recall is substantially better in the spatial path version, with an improvement of something like 1-3 sentences compared with the nonsense version (Baddeley & Lieberman, 1980; Logie, 1986).

The observed improvement in sentence recall when supplemented with spatial directions is taken as evidence that applying spatial imagery to verbal sequential memory enlists extra resources beyond those engaged during rote verbal memorization. Researchers have used various dual-task manipulations to attempt to reveal the nature of these resources. Baddeley and Lieberman (1980) juxtaposed spatial path and nonsense Brooks tasks with a spatial tracking task in which participants tried to keep a flashlight shining on a beeping photocell attached to a pendulum, or alternately with a brightness judgment task. Baddeley, Grant, Wight, and Thomson (1975) paired the same Brooks tasks with a spatial tracking task with visual rather than aural feedback. Spatial tracking, whether by visual or aural cues, significantly reduced participants' scores on the spatial path version of the Brooks task, but did not significantly impair performance on the nonsense version. Performing brightness judgments on the other hand did not impair performance on the spatial-path Brooks task, but did significantly impair memory for the nonsensical sentences. In contrast though, two similar investigations did find that brightness judgments impaired recall in a spatial-path Brooks task (Beech, 1984; Quinn, 1988). The case for selective interference with Brooks-task visualization is therefore inconsistent.

Logie, Zucco, and Baddeley (1990) used spatial-path and nonsense Brooks tasks as concurrent processing tasks during verbal and spatial memory span procedures. Logie et al. observed a clear pattern of domain-specific selective interference: the verbal memory span procedure impaired the nonsense Brooks task more than it impaired the spatial path Brooks task, while the reverse pattern was observed with the spatial memory span procedure. However, both span procedures impaired Brooks task performance, regardless of version, by an average decrement of at least 25%. Likewise, though the spatial-path Brooks task affected spatial memory spans more than the nonsense Brooks task and the nonsense Brooks task impaired verbal memory spans to a greater extent than the spatial-path Brooks task, combining either span procedure with either Brooks task provoked massive costs to memory span. At best, memory span during a secondary Brooks task was an average of 63% of span without a concurrent task. These results suggest both domain-general and domain-specific sources of disruption to the use of imagery in the Brooks-task, which Logie et al. attributed to joint use of the domain-specific and domain-general modules posited in the multi-component working memory model.

A summary of which secondary tasks affect recall in the Brooks task is given in Table 1. The spatial path and nonsense versions of the Brooks matrices tasks appear to vary in their susceptibility to different sources of interference. However, these findings do not clearly map onto expectations generated by the idea that there are distinct verbal and visual-spatial short-term memory resources. Though the nonsense Brooks task is intended to assess rote verbal serial memory, it is sometimes significantly affected by a brightness judgement task, which would not have been thought to rely much, if at all, on verbal processes. Efforts to show that only *spatial*, but not *visual*, secondary tasks interfere with utilizing a spatial imagery strategy in this task also produced inconsistent results. Though spatial tracking had little or no detectable effect on the nonsense Brooks task, both spatial and verbal short-term memory loads substantially impaired nonsense Brooks performance. Similarly, both verbal and spatial memory loads substantially impaired performance on a spatial-path Brooks task. Detrimental effects of memory loads on Brooks task performance are perhaps unsurprising, as both tasks require participants to remember lists of verbal information. However, patterns clearly show that interference by domain does not operate with perfect selectivity. It is also worth considering whether performance on any verbal memory task, however reliant on spatial imagery, is ideal for reasoning about the operations of a hypothetical visual-spatial short-term memory system.

Use of peg-word and Method of Loci mnemonic strategies. If the spatial-path version of the Brooks task involves spatial (but not visual) imagery, then a way to assess the effects of visual (but not spatial) imagery on verbal recall is also needed. The peg-word mnemonic strategy fills this void. Participants are given lists of concrete, imageable words to remember, along with the suggestion to visualize each word with another concrete, imageable noun that is constantly tied to the same serial position (e.g., one-bun). When instructed to use this technique, participants remember about 1.5-3 words more than participants who were not told to engage in an imagery technique (Logie, 1986).

As with the advantage observed in spatial path compared with nonsense Brook matrices tasks, dual-task methods can be employed to learn what sorts of materials prevent the peg-word mnemonic advantage from appearing. Again, observed patterns do not consistently support hypotheses about selective interference. Logie (1986) paired rote and peg-word mnemonic serial recall with passively viewing matrices, colored squares or line drawings, passively listening to irrelevant speech, and making judgments about matrices. Except for passive listening, all of these secondary task conditions provoked a decrease in recall in the peg-word mnemonic conditions. Quinn and McConnell (1996) found that irrelevant pictures disrupted recall using both rote and peg-word strategies. McConnell and Quinn (2000) found that only dynamic, but not static, visual information disrupted use of a peg-word mnemonic strategy, and that the extent of interference to the use of the peg-word strategy increased with the amount of movement and the size of the display (McConnell & Quinn, 2004). Baddeley and Lieberman (1980) paired rote and peg-word mnemonic recall tasks with a spatial tracking task, and found that concurrent tracking reduced recall in the peg-word imagery condition but not in the rote recall condition. Increasing the similarities between the mnemonic strategy and the concurrent task predictably decreases the effectiveness of the mnemonic strategy. Baddeley and Lieberman demonstrated this by replacing the peg-word strategy with a method of loci strategy in which participants were given a common path through campus and encouraged to encode list items with respect to various landmarks along this path. The effect of concurrent spatial tracking on recall grew larger when paired with this spatial mnemonic method than it appeared with the peg-word method. Overall though, evidence of domain-specific selective interference with use of visual or spatial imagery appears haphazardly. Significant detriments to strategy use often occur where they should not if one posits distinct mechanisms for holding verbal, visual, and spatial memoranda.

The findings from papers investigating dual-task interference with visualization strategies are summarized in Table 1. Taken together, these results suggest that various cognitive processes may be enlisted in support of verbal memory, and that these processes can be disrupted by concurrent tasks that engage similar processes. Generally (but not universally), the more overlap between the mnemonic strategy and the distractors, the less effective the mnemonic strategy would prove. These results suggest some degree of distinctness between auditory-verbal processes, spatial processes, and visualization processes, which any model of working memory must account for. However, they do not strongly suggest independence of visual, spatial, and non-visual cognitive processes. Models of working memory must also have a clear method for accounting for this apparent dependence.

Early visual-spatial recognition memory research

So far, the evidence described (and indeed, the main body of evidence upon which the initial descriptions of the visuo-spatial sketchpad were based) pertains exclusively to tests of serial verbal memory, an odd situation for theorizing about a buffer meant for holding visual images or spatial sequences. Early evidence from visual recognition memory tasks was also available at this time, and already suggested that verbal and visual-spatial short-term memory might operate differently. Phillips and Christie (1977a, 1977b) tested memory for sequences of grid patterns. Participants were presented with a sequence, and then performed a sequence of recognition judgments: beginning with the final pattern, they were asked to judge whether a test pattern was either identical to or different from the observed pattern. Recognition judgments were likewise elicited for the remainder of the presented patterns in reverse order. As with verbal serial memory, the data showed a clear spike in recognition accuracy for the final item in the list. This recency effect was present in lists ranging in length from 1 to 8 items. Unlike verbal serial recall however, the recency advantage was always confined to a single pattern, and there was no evidence for primacy effects (i.e., superior performance for the first items presented). However, because primacy effects have been demonstrated with other sorts of visual materials and tasks (e.g., Cortis, Dent, Kennett, & Ward, 2015; Guérard & Tremblay, 2008; Logie, Saito, Morita, Varma, & Norris, 2016; Morey and Mall, 2012; Morey & Miron, 2016; Parmentier, Tremblay, & Jones, 2004), and because comparable serial position curves appear when comparable response methods are used (e.g., Jones, Farrand, Stuart, & Morris, 1995; Ward, Avons, & Melling, 2005), it is likely that their absence here is due to other factors, perhaps interference from attempting to maintain such a long list of patterns, or differential interference from reverse-order testing.

Notably, Phillips and Christie's work suggested that visual memories might be quite susceptible to general interference from non-visual sources, in contrast with verbal memories, which seem to be fairly resilient to non-specific interference. Phillips and Christie (1977b) made an effort to discern precisely which sorts of processes interfere with the robust recency effect in visual recognition tasks. They found that tasks requiring some processing or judgment significantly reduced the recency effect, regardless of whether those tasks involved auditory or visual presentation of information, while passive distraction, such as observing a visual suffix, or listening to or reading off a sequence of digits, had no discernible effect on visual recognition accuracy. These experimental investigations of serial visual memory showed no evidence that visual-spatial memories are impaired more by visual or spatial distractors than by a verbal concurrent task: extent of interference was consistently determined by the cognitive demands of the secondary task, not the sensory domain in which the stimuli were presented or presumably represented.

Limits these findings placed on working memory theory

The evidence described so far implies that memoranda may be maintained in visual formats. Combined with the wealth of evidence that verbal memories can also be maintained in phonological code, it furthermore seems clear that mnemonic representations can be encoded in multiple domain-specific formats. Additionally, there is unambiguous evidence that distracting material provokes greater interference when it shares the domain-specific format of the memoranda (e.g., Logie, Zucco, & Baddeley, 1990). Furthermore, there are neuropsychological cases in which verbal but not visual short-term memory seems to be impaired, and vice versa (e.g., De Renzi & Nichelli, 1975), and for verbal short-term memory deficits, some degree of anatomical specificity is apparent. Taken together, these are the findings pointing towards a system in which short-term maintenance is accomplished via domain-specific pools of resources (e.g., Baddeley, 1986; Gathercole, 1994).

However, as Phillips and Christie (1977b) put it, ". . . the question as to whether there are separate mental mechanisms for thinking in words and pictures is sometimes approached by treating it as identical to the question as to whether words and pictures have separate forms of representation. . . ." (p. 638). Does the conclusion that there are separate mental mechanisms for thinking in words versus thinking in pictures follow so confidently from this evidence? Put another way, could this evidence be explained as well by a model that allows for both verbal and visuo-spatial representations, without specifying that those representations must reside in distinct short-term stores? The evidence I have described so far, which was cited in the earliest expositions of the visuo-spatial sketchpad as the groundwork for the model, cannot unambiguously support a separate systems account. This evidence was interpreted as reflecting a distinct visual-spatial short-term memory system because another system, the verbal system, was already assumed. Some module capable of representing visual images was needed, and this module was assumed to support visual memories exclusively.

An equally valid solution to this problem might have been to propose an additional domain-general short-term memory buffer to complement the verbal system. Distinguishing between the possibility that representations formed using domain-specific codes are maintained in specialized buffers rather than with domain-general, multi-purpose cognitive resources became even more important when domain-general storage resources were added to the multi-component model of working memory later, with the proposal of an *episodic buffer* component (Baddeley, 2000). The logical addition of a component for maintaining non-verbal, imagery-based representations might have seemed necessary in a model that was otherwise only capable of holding phonological code, but if general-purpose storage is also included, is the specialized visual system redundant? The episodic buffer (Baddeley, 2000) was intended to provide a means of retrieving long-term knowledge into the working memory system for immediate use, as well as for creating links between features encoded in verbal versus visual or spatial codes (for instance, pairing names with faces, or location names to coordinates on a map). Baddeley allowed for both of these functions by adding a store capable of representing information in any sort of code. The acceptance of the need for some general-purpose storage in a working memory calls all previous interpretations of selective interference during dual-task paradigms into question. Even supposing that this body of evidence unambiguously showed that verbal information strictly impaired verbal memories and visual-spatial information strictly impaired visual-spatial memories, such a double dissociation could be equally well explained by supposing one specialized storage buffer and one general storage buffer as by supposing two specialized storage buffers. Now that general storage is acknowledged, it is reasonable to consider whether either of the specialized stores have become unnecessary baggage.

Much more evidence bearing on visual short-term memory is now available to inform debate about whether both visual and verbal storage must be posited in models of working memory, but in order to be able to fairly consider it, we must attempt to view and weigh it without the unnecessary aim of forcing it to fit into the modules specified by the multi-component working memory model. Instead, we should use the assumptions reasonably arising from the multi-component working memory system to predict the patterns that should emerge, given the specific proposals of that modular system. In the next section, I describe the patterns that I believe should appear in data if a specialized visual-spatial short-term memory buffer were in operation. I have aimed to focus my expectations so as not to place limits on what other components a multi-faceted cognitive system may or may not contain. In the next section, I describe these patterns, and subsequently review evidence in two literatures that purportedly serve as the empirical basis for modular short-term memory stores: neuropsychological case evidence of selective impairments to visual or spatial short-term memory, and dual-task interference as measured by costs to accuracy in visual or spatial memory tasks. This thorough review makes quite clear that the accumulated evidence about what interferes with visual memory does not provide unequivocal support for a distinct visual short-term memory module, even though it has been claimed repeatedly to support this position (e.g., Baddeley, 2007; Gathercole, 1994; Logie, 2011). In the discussion, I will describe what this evidence suggests that we would need to assume about the functioning of a hypothetical specialized visual short-term memory system. Beyond that, I will argue that the accumulated research fails to distinguish domain-specific from domain-general memory storage, and that we therefore have no compelling reason to assume a specialized visual short-term memory system at all. I believe that the available evidence is inconsistent with the proposition of a distinct visual short-term memory store, and that we ought to consider alternative ways of explaining why memory performance tends to be better with cross-domain task combinations than within-domain task combinations, giving these alternatives at least as much credence as is given to the assumption of a specialized visual short-term memory system .

Evidence that would support the proposition of a visual-spatial short-term memory buffer

A multi-component working memory system including both verbal and visuo-spatial short-term storage is already widely assumed even though the evidence supporting such a system could be explained equally well with alternative constructions. How could we decide which of several possible frameworks best fit the available evidence? Baddeley (1992) admits that a model as complex as the comprehensive multi-component model of working memory is unlikely to be strictly falsifiable. If only two components were proposed, then the model could be evaluated by creating experimental circumstances intended to reveal double dissociations, and evaluating the predominance and strength of these patterns in the data (although this method is not without controversy; see Dunn & Kirsner, 2003). Although more than two components are assumed, searching for double dissociations is one of the experimental strategies that has been applied to assess various pieces of the multi-component model. However, because cognitive resources besides the ones explicitly tested could be contributing to task performance (e.g., Logie, Saito, Morita, Varma, & Norris, 2016), finding experimental dissociations does not provide definitive support for the hypotheses tested. For instance, the multi-component model now includes at least three components capable of storage: the phonological store, the visual cache, and the general-purpose episodic buffer. Observing a pattern in which verbal tasks interfere more with verbal memory and visuo-spatial tasks interfere more with visuo-spatial memory cannot confirm that there are verbal and visuo-spatial short-term stores, because this apparent selectivity could just as well arise from making use of a domain-specific resource (e.g., the verbal or the visual-spatial buffer) plus a domain-general resource capable of accommodating either sort of code (e.g., the episodic buffer). All three components are not needed to explain dissociations.

Assuming more than two components in the working memory model, especially when one is as versatile as the episodic buffer, makes it impossible to discover an experimental dissociation that demands any single specialized component. Instead, we must delimit a network of anticipated evidence that would arise assuming the proposed multi-component system. What combination of evidence should be taken as converging upon the need for a specialized visuo-spatial short-term memory system? Such a body of evidence should go well beyond showing that memoranda can be maintained with visual and spatial features intact, because this observation alone is insufficient for declaring that these visual and spatial features are maintained within their own specialized sub-system (Phillips & Christie, 1977b). What is required is evidence that persuasively eliminates the possibility of visual memoranda relying on general-purpose resources for storage. Such evidence is crucial for converging on the unparsimonious idea that working memory must include both domain-general stores and some variety of domain-specific stores, including specifically verbal, visual, and spatial ones. Although such a body of evidence is often assumed, review of the primary studies cited in support of the visuo-spatial sketchpad component makes clear that many desirable pieces of evidence are missing and that inconsistent pieces of evidence, most notably that verbal tasks consistently interfere with visual memory (Phillips & Christie, 1977b), are given little weight.

Possibly, researchers hastily concluded that there must be a specialized visual short-term memory system because there are a handful of neuropsychological patients who present with apparent deficits to visual or spatial short-term memory. If there were a visuo-spatial short-term memory buffer, one might expect to occasionally observe a patient presenting with impaired visual or spatial short-term memory while also demonstrating intact short-term memory for verbal materials, along with intact visual perception and intact long-term memory for imagery and routes learned prior to onset of the neuropsychological complaint. Additionally, such a model patient should *not* show deficits in general cognition that cannot be linked directly to visual short-term memory; otherwise, it would be impossible to say with conviction that any visual short-term memory deficits occur because a specialized system is defective and not because a more general deficit has a greater impact on visual than verbal short-term memory. I shall begin by examining evidence from cases in which visual or spatial short-term memory is impaired, and consider whether any of these cases demonstrate the degree of selective deficit necessary to support claims that an exclusively visual short-term memory system has been damaged. To summarize, though a few instances of patients suffering from apparent visual short-term memory deficits have been reported, each patient shows patterns of deficits that are inconsistent with the idea that a visual short-term memory store has been exclusively affected. The data I shall review therefore does not convincingly eliminate the possibility that something more general that affects visualization is damaged in these patients, and casts doubt on the argument that these patients prove the existence of visual or spatial short-term memory stores.

Since the relevant neuropsychological cases do not unequivocally support a distinct visual-spatial short-term memory system, then the accumulated experimental evidence should be critically evaluated against benchmarks that would provide stronger evidence for such a system. In order to meet the criteria I shall propose, any task in question should convincingly isolate maintenance of visual or spatial materials; otherwise, there is all too much reason to suppose that cognitive processes other than those proposed to be part of any visual-spatial short-term memory system influence performance. Much of the evidence described above as supporting the initial proposal of a distinct visual-spatial short-term memory system already lacks this level of rigor; Brooks matrices tasks and mnemonic strategy induction are manipulated with the intent of enhancing verbal memories, not measuring visual or spatial memory directly. Recognition of abstract visual images or patterns and recall of spatial sequences come much closer to this goal, but little work of this nature was available to influence theorizing about a visual-spatial short-term memory system until after the theoretical visual short-term memory system was proposed and presumed.

Furthermore, it is necessary to consider whether the manipulation designed to interfere with maintenance of the visual materials is likely to act on their maintenance, and not only their encoding. Some evidence arising from these mnemonic strategy manipulations already casts doubt on the notion that these effects arise during storage of the memoranda. Quinn and McConnell (2006) manipulated whether dynamic visual noise, which is a changing visual signal that requires no active response from the participant, occurred only during encoding or only during retention. Dynamic visual noise had previously been shown to disrupt use of the peg-word mnemonic strategy (McConnell & Quinn, 2000; 2004; Quinn & McConnell, 1996), but had been applied during both encoding and maintenance. Quinn and McConnell found that dynamic visual noise only impaired use of this strategy when applied during encoding. Though this work has been used to theorize about a specifically visual short-term memory store, one should not conclude that a process that uniquely disrupts *encoding* of visual information has disabled a visual storage buffer. If we are interested in discerning the operations of a module needed to *maintain* memoranda in visual codes, then we need to place special emphasis on data arising from designs that isolated interference occurring during maintenance.

Assuming that a task fairly isolates maintenance of visual-spatial memoranda, what patterns of results would suggest a specialized and independent visual-spatial short-term memory system? First, it should be the case that some amount of visual or spatial material may be maintained without *any* dual-task cost. Baddeley and Hitch (1974) found virtually no interference to task accuracy between maintaining short verbal lists and performing a concurrent reasoning task. Likewise, in order to suppose an independent visual-spatial store it should be possible to demonstrate that some amount of information held in a visual or spatial format can be maintained without cost from a concurrent task that does not also make use of the visual-spatial short-term memory system. Even if it is a small amount of visual material, some visual material should be impervious to cross-domain interference. Moreover, if this visual-spatial store is to be believed to be distinct from sensory or long-term memory (e.g., Sligte, Scholte, & Lamme, 2008), then experimental methods must be sufficient to rule out the possibility that any resistance of these items to general interference is actually due to representation in sensory or long-term memory. I shall examine evidence from studies that measure visual memory in the presence of some distracting task or stimulus to learn what sort of information can be processed or stored simultaneously with visual information, without leading to decreases in visual memory performance. I highlight evidence from my own work, which has been explicitly designed to isolate maintenance processes, and then broaden consideration by meta-analyzing the dual-task visual-spatial memory literature. Both strands of enquiry show that even small visual memory loads are robustly affected by the performance of any cognitively-demanding secondary task, regardless of whether the secondary task requires visual or non-visual processes.

Much research meeting these criteria has been published since the proposal of the visual-spatial sketchpad components, but it has not been thoroughly reviewed with the goal of discerning whether a dedicated visual-spatial memory store is necessary for explaining emerging patterns. Rather, the existence of such a store has been supposed a priori on the basis of the evidence described above, and contradictory evidence has been dismissed with ad-hoc explanations (e.g., invoking the possibility of verbal recoding). By declining to assume the need for a specialized visual-spatial store, I will allow a rather different picture of a working memory system to emerge. These emerging ideas are broadly consistent with emerging ideas about working memory and memory theory more generally, and arguably more consistent with evidence from neuroscience than the multi-component working memory model (cf. D'Esposito & Postle, 2015). My examination of this evidence challenges multiple-component working memory theorists and those applying this working memory theory to practical problems to overcome the rut that assumptions about modularity has mired us in, and shift towards imagining alternative explanations.

Neuropsychological cases of visual and spatial short-term memory deficits?

Supporters of the multi-component model frequently invoke neuropsychological case evidence to back up claims of distinct verbal and visual or spatial short-term memory systems (e.g., Baddeley, 2012; Gathercole, 1994; Repovš & Baddeley, 2006). Compelling evidence from neuropsychological case histories would provide a strong reason a priori to suppose specialized short-term memory components, even if evidence from the experimental literature remained ambiguous. Neuropsychological evidence is especially helpful for this problem if you believe that elements of a working memory system may be flexibly deployed based on strategic choices. In any experimental paradigm, other resources apart from the targeted specialized stores may be applied, stymieing our attempts to truly isolate a domain-specific store (Logie, 2011). Convincing patient evidence that converges with experimental evidence would alleviate this concern.

However, a major problem with this reasoning is that a compelling case of a patient with a clearly selective loss of visual-spatial short-term memory has not been documented. Several cases have been reported that show some degree of visual or spatial deficit, and certainly there are neuropsychological disorders that affect visual thought much more than non-visual thought (e.g., Lissauer & Jackson, 1988; Shallice & Jackson, 1988; Tippett, Miller, & Farah, 2000; Zeman, Dewar, & della Sala, 2015). However, the loss of function that would be expected if a visual short-term memory buffer were selectively damaged would not merely entail an inability to imagine visual information: taken at face value, the extant cases of auditory short-term memory loss present a pattern in which short-term memory is impaired with auditory but not visual presentation of exactly the same information, while also showing that long-term learning based on auditory input is largely unaffected. Few of the purported cases of visual short-term memory deficit show the degree of specificity to visual information and short delays displayed by K.F. (Shallice & Warrington, 1970; Warrington & Shallice, 1969) or P.V. (Basso, Spinnler, Vallar, & Zenobio, 1982; Vallar & Baddeley, 1984) with auditory information. These patient reports often fall short of ruling out deficits to visual or spatial sensory or long-term memory (note though that a skeptical case can also be made that auditory short-term memory patient cases do not actually reflect a short-term memory impairment; Caplan, Howard, & Waters, 2012). I will describe examples of these cases and then analyze the contexts in which they are cited in support of modularity in working memory to reveal the discrepancies between the existing evidence and the theoretical positions the evidence is meant to support.

I identified cases of apparent visual and spatial short-term memory loss primarily via previously published literature reviews in support of the multi-component working memory model (e.g., Baddeley, 1986; Baddeley, 2012; Gathercole, 1994; Repovš & Baddeley, 2006). Because these patient cases provided such important evidence informing the development of this model, I expected that the best-documented and clearest cases of visual and spatial short-term memory loss would be cited and mentioned by these sources. In reviewing these primary case reports, I found additional instances of relevant patient cases which I also considered. Table 2 lists these cases, including a brief description of any reported locus of anatomical damage, and a blunt assessment of the reported evidence on the patient's verbal, visual, and spatial short-term memory tests, and visual or spatial long-term memory tests. Because the manner of testing differed substantially across papers, I did not include mean performance values. The selected cases I describe in detail differ from the ones I merely cite in that they include a sufficient battery of tasks to assess whether short-term memory was impaired while long-term memory was intact, and similarly to assess whether verbal memory was intact despite deficits to visual and/or spatial memory. However, in contrast to the fairly consistent batteries of tasks performed on auditory case patients like K.F. and P.V., testing of these patients with visual and spatial cognition deficits has been haphazard. Some cases report very little evidence from standardized tasks, including only a mix of observations from what appear to be ad-hoc tests (Ross, 1980). Others report standardized test scores showing a mixed profile of possible deficiencies (e.g., Hanley, et al., 1990; Wilson, Baddeley, & Young, 1999), by no means limited to visual or spatial short-term memory. I restricted my analysis to cases that did not report visual or spatial short-term memory loss in the presence of another diagnosed disorder, unless a particular case figured prominently in at least one of the literature reviews describing the developing visuo-spatial sketchpad model (e.g., Wilson et al., 1999).

A case of both visual and spatial memory deficits

At the time of testing, E.L.D. was a 54-year-old, independent, community-dwelling female who had suffered an aneurysm at the age of 49 (Hanley, Young, & Pearson, 1990). E.L.D. spontaneously complained of having become “generally forgetful”. She reported problems with recognizing faces of people met after her illness, and of having difficulties finding her way around her new neighborhood and flat. On preliminary perceptual tests, E.L.D. performed normally on object recognition and face comparison tasks, despite experiencing impaired color vision and contrast sensitivity. E.L.D.'s post-morbid intelligence test scores were average or above average overall, but she attained lower-than-expected scores on particular episodic memory sub-tests, including paired associate word learning. While she performed well on a word recognition task, she performed below average on a face recognition task (developed by Warrington, 1982) and much worse than a control sample on experimental face recognition tasks when the to-be-remembered faces were unknown to her prior to her illness. Her ability to recognize famous names was comparable to controls' performance regardless of whether the names became famous before or after her illness. E.L.D. also demonstrated a deficit compared with controls in recognizing unfamiliar voices.

While this evidence does suggest a predominantly visual impairment, it is not clear whether short-term memory specifically is affected. Hanley et al. (1990) report several experiments in which E.L.D.'s recognition of faces was tested. When E.L.D. was required to choose which of 12 faces was recently presented, she performs much worse than controls; however, when E.L.D. performed a task that required her to indicate which of two faces or objects she had seen recently, she performed nearly as well as controls. This suggests a possible deficit during retrieval under conditions of high interference, which may not be exclusive to visual images. Hanley et al. also tested whether E.L.D. could recognize precisely which view of an object had been presented. E.L.D. appeared to show some deficit in recognizing the precise view of the person or object compared with control participants, but note that E.L.D. performed this task at a delay of one month, a substantially longer delay than the control sample experienced, and a delay far beyond what can reasonably be considered “short-term” memory. This difference in measurement alone is sufficient to explain any difference in performance between E.L.D. and the healthy control sample. Altogether, one could conclude that E.L.D. demonstrated recognition memory for visual materials comparable to controls when the test decisions were limited to a two-choice scenario, suggesting that her deficit might not have been in storing visual images per se.

E.L.D. also showed deficiencies in spatial memory, as measured by the Brooks matrices task and the Corsi blocks task. E.L.D. could recall Brooks' sentences perfectly up to series of 5, but made substantially more errors than control participants on longer lists. Similarly, E.L.D. performed as well as all control participants on recall of sequences of 3-4 Corsi blocks, but committed many more errors than control participants on longer sequences. She also performed poorly on mental rotation tasks. On verbal serial recall tasks, E.L.D.'s performance was similar to that of control participants (Hanley, Young, & Pearson, 1991).

Though Hanley et al. (1990; 1991) demonstrated that E.L.D.'s deficiencies were more pronounced in visual or spatial than in verbal memory, the pattern of her deficits and preservations is difficult to square with hypothesized damage to the visual-spatial sketchpad as it is often described (Beigneux, Plaie, & Isingrini, 2007; Doherty-Sneddon, Bonner, & Bruce, 2001; Turriziani, Carlesimo, Perri, Tomaiullo, & Caltagirone, 2003). E.L.D. could not learn to associate new faces with their names and occupations, but she had little difficulty recognizing which of two unfamiliar faces she had encountered in a recent experimental session. Her spatial sequence memory was poorer than controls but perfect for short lists, presumably of the length that would be maintained in a visual-spatial short-term memory buffer. Her performance of a verbal memory task with a spatial imagery component was likewise perfect for short lists, but deficient compared to controls' performance as sequence length increased. While she was unable to successfully implement mnemonic strategies based on mental imagery, she also had trouble implementing strategies based on verbal repetition. Despite pronounced difficulties with particular visual tasks, E.L.D.'s established difficulties recognizing new voice timbres, learning verbal paired associates, and implementing verbal strategies clearly suggests that her impairments extended beyond visual memory specifically. These deficits implicate episodic memory, auditory memory or audition, and possibly even implementation of verbal rehearsal. Moreover, within her problems with visual memory, short-term memory is not uniquely implicated based on the available evidence.

Much of the nuance inherent in E.L.D.'s case is lost in the way that her case reports are cited and summarized. Frequently, the separate papers describing E.L.D.'s memory for faces (Hanley, Pearson, & Young, 1990: cited 83 times according to Web of Science, after limiting results to peer-reviewed articles in the domain of psychology and excluding authors' self-citations) and E.L.D.'s apparent dissociation between serial verbal and spatial memory (Hanley, Pearson, & Young, 1991: cited 16 times using the same limitations described above) are cited in isolation, and sometimes the statement for which they are cited is inconsistent with E.L.D.'s complete range of deficits. For example, the paper comparing E.L.D.'s spatial and verbal serial memory has been cited as evidence of dissociations between spatial memory and object memory at least 12 times, despite the evidence that E.L.D.'s memory for sequences of faces as well as spatial locations is poorer than controls' performance. However, E.L.D.'s preserved memory for judging which of two faces she recently saw (Hanley, et al., 1990) does hint that any short-term memory deficit for visual materials might be confined to memory for their serial order. Considering both papers, E.L.D.'s case is more frequently cited as evidence favoring the hypothetical dissociation between a phonological loop and a visuo-spatial sketchpad (across both papers' citations, 28 occurrences). While it was clearly demonstrated that E.L.D. performs serial verbal memory tasks as well as controls and visual or spatial serial memory tasks worse than controls, her entire portfolio of cognitive deficits includes many examples of problems that are inconsistent with the idea that she suffers from an impaired visual-spatial short-term memory buffer, most especially her intact ability to detect which of two faces were shown on a recent trial. These complexities, which should prevent glib conclusions about a clear dissociation isolating visual-spatial short-term memory, are acknowledged in remarkably few published references to E.L.D.'s case (e.g., Borgo, Giovanni, Moro, Semenza, Arcicasa, & Zaramella, 2003; Della Sala, Gray, Baddeley, Alamano, & Wilson, 1999; Jonides, Lewis, Nee, Lustig, Berman, & Moore, 2008).

E.L.D.'s case presents a complex mix of deficits. Though the evidence available suggests that her memory for visual and spatial materials is more drastically affected than many other cognitive processes, sufficient evidence of deficits in tasks that could not be dependent on visual or spatial short-term memory make clear that she is not an example of someone with a selectively impaired visual short-term memory system. Her impairments appear to leave verbal serial short-term memory unaffected, justifying the conclusion that verbal serial short-term memory relies on processes beyond those needed for visual or spatial cognition. However, her pattern of deficits cannot support a model of working memory that separates visual short-term memory from other domain-general processes because her deficits include a variety of non-visual memory problems. The pattern of deficits shown by E.L.D. is certainly not the reverse of the pattern shown by so-called auditory short-term memory patients, who could learn aurally-presented verbal information with long delays (Basso, et al., 1982; Warrington & Shallice, 1969). E.L.D.'s case thus does not require that a working memory system include a specifically visual or spatial short-term store.

Cases of visual imagery deficits

Of the few proclaimed cases of visual short-term memory deficits, the most vivid and detailed is that of L.E. (Wilson, Baddeley, & Young, 1999). L.E. was a sculptress suffering from systematic lupus erythematosus, who reported experiencing difficulties with memory and wanted advice on how to handle these difficulties. Though she was dissatisfied with her abilities, scores on standard neuropsychological tests showed nothing alarming: L.E. scored highly on assessments of intelligence and within normal ranges on a number of memory tests. Her insistent complaint that she "can't visualize where things go. . . (or) . . . draw on my fund of knowledge" (p.122) led to extensive testing of visual-spatial abilities, which confirmed problems with visualization. L.E. performed below normal controls on tests of visual recall and recognition (including famous face visualization tasks; Young, et al., 1996), but similarly to controls on perceptual matching tasks. She also performed normally on expression imagery tasks (e.g., describing what facial expressions corresponding to various emotions look like), but the authors note that this task could be performed using motor reenactments rather than visual imagery. Most strikingly, L.E.'s sculptural style changed. Before her injuries, she sculpted life-like subjects, but afterwards her style grew abstract. She attributed this to difficulties holding an image in mind, and described anecdotes in which she committed obvious, unintended errors in depiction, such as sculpting a person with four legs.

While it seems clear that something happened to L.E.'s visual-spatial abilities, it is difficult to pin this on visual short-term memory specifically. Much of the evidence comes from tasks that require retrieval of an image from long-term memory (for instance, of a famous face or a familiar animal) and subsequent description of it (Wilson et al., 1999). These tasks clearly draw upon learned information, and thus do not necessarily isolate a visual short-term memory system. Another patient diagnosed with "recent visual memory loss" (Ross, 1980) scored perfectly on a task in which novel patterns were studied and reproduced after a 5-second delay; this procedure would seem to isolate visual short-term memory from long-term memory, yet the patient could do it. L.E. functioned well in daily life, had no observable object agnosia, and could recognize the same items or faces on a matching test. We can thus deduce that her perception of visual information was more or less intact, and that she could somehow access long-term knowledge about what things look like. However, we do not know whether her visual long-term knowledge remained as detailed as ever. With the reported tests, we are limited to blunt deductions about what went wrong: L.E. could not imagine visual imagery, but whether this was due to trouble retrieving visual details, using those details to generate an image, or keeping a generated image active is unclear. To say that this case illustrates a deficit in the visuo-spatial sketchpad does not in itself suggest much detail about what the visuo-spatial sketchpad is meant to do. Today, L.E. might instead be described as experiencing an abrupt onset of aphantasia, which is characterized by inability to experience mental imagery (Zeman, et al., 2015).

Further valuable information comes from L.E.'s performance on tests not directly connected to visualization. First, L.E.'s verbal short-term memory scores were abnormally low. Furthermore, though her performance on episodic memory tasks and executive functioning tasks are within normal ranges (or nearly so in some instances), it is acknowledged that in L.E.'s case, this is weak evidence for a lack of impairment to memory and executive functions generally (Wilson, et al., 1999). L.E.'s high intelligence test scores contrast with her mediocre memory and executive functioning scores, suggesting that she might have experienced reduced memory ability after the onset of her illness despite her generally good performance compared to the population at large. Although less detail about the tasks they performed and their scores is available, evidence from other patients with reported visual imagery deficits likewise suggests that supposed visual short-term memory deficits did not occur in isolation. For example, Monsieur X (as described by Young and van de Waal, 1996) not only complained about his loss of previously "photographic" memory, but also his inability to think fluently in his second language since the onset of his illness. While evidence that visual memory deficits tend to co-occur with other impairments does not falsify the idea of a specialized visual short-term memory buffer, these patterns are likewise expected from a hypothetical system in which effective visualization requires domain-general cognitive resources.

Cases of spatial memory deficits

The most complete case descriptions of patients presenting with spatial short-term memory span deficits are those of M.V. (Carlesimo, Perri, Turriziani, Tomaiulo, & Caltagirone, 2001) and G.P. (Bonni, et al., 2014). Other reports of spatial short-term memory deficits come from DeRenzi and Niccheli (1975), Lepore, Celantano, Conson, and Grossi, 2008; Luzzati, Vecchi, Agazzi, Cesa-Bianchi, and Vergani (1998), and Ross (1980), but the battery of tests given to M.V. and G.P. is more comprehensive and appropriate for revealing selective deficits to spatial short-term memory than the collections of measures reported elsewhere.

Though demonstrating normal intelligence and normal-range performance on visual perception tests, M.V. showed poor forward spatial span. Comparisons of serial order memory spans with verbal, visual, and spatial memoranda showed that M.V. was deficient compared to controls only for to-be-remembered spatial location sequences. For both M.V. and the control participants, performance with verbal materials exceeded that with visual materials, particularly the non-spatial visual memoranda. Various evidence suggested that M.V. could learn spatial relations and paths given enough time: he could accurately perform mental rotations, albeit much more slowly than control participants, and he had no discernible difficulties learning his way around novel environments. Another report summarized by Carlesimo et al. indicated that M.V. could learn supra-span Corsi-block sequences given sufficient time (Spinnler & Tognoni, 1987). However, real-life navigation and mental rotation are difficult to compare directly with the measures of spatial short-term memory, and even repetitive Corsi sequence recall might isolate processes other than retention alone. While Carlesimo and colleagues emphasize the specificity of M.V.'s spatial short-term memory deficit, he also showed fairly weak (though apparently normal) performance given his high intelligence scores on some non-spatial visual memory tasks and verbal long-term memory tasks. His deficits also included face recognition, where his scores fell in the <5 percentile compared to controls. In other patient cases, impairments in recognizing faces were considered evidence of a visual memory deficit, not a spatial memory deficit.

G.P. also presents with an apparently selective deficit for serial spatial short-term memory, but in G.P.'s case, immediate recall performance was unimpaired while performance after delays of 10-20 seconds decreased more rapidly for G.P. than for healthy controls (Bonni, et al., 2014). Comparing G.P. with M.V., Bonni et al. argue that G.P.'s spatial short-term store is unaffected, but that mechanisms needed to keep spatial memories active are impaired. However, the more comprehensive description of methods provided in the report of patient G.P. makes clear that differences between the verbal, visual, and spatial serial memory tasks extend beyond the domain of the memoranda, muddying interpretation of selective impairments. Presumably, these task descriptions also apply to M.V.'s case. In the visual task, stimuli were delivered via computer whereas in the other two tasks, stimuli were presented by an experimenter. Each of the three memory tasks also differs in response conditions. In the verbal serial recall tasks, participants generated both the verbal items and their serial order with spoken responses. In the spatial tasks, participants chose the spatial locations in order from a set of 9 options, regardless of list length. This is true of Corsi-block task administration generally. In the serial visual tasks, participants were shown the shapes presented on that trial in a random order, and participants reconstructed the order in which they appeared. These response conditions are different enough to stymie straightforward interpretation: in the visual task, participants were only confronted with the relevant memory items from the current trial at test, and were confronted with fewer potential selections. Some sorts of mistakes (e.g., prior-list intrusions) were impossible to commit in the visual task, but possible in the other two tasks. The verbal and spatial tasks additionally differed in whether the items were self-generated or not. Because of the overt presentation of all the choices at test, the spatial task may have required the greatest ability to resist interference arising from considering response options. Though task domain may be the most vivid difference between these three tasks, they differ in other non-trivial ways that should preclude declaring that spatial serial short-term memory was selectively impaired in G.P. and M.V.

All considered, evidence for a specialized spatial short-term memory deficit appears stronger than evidence for a visual short-term memory deficit, but hardly decisive. As with previously described cases, though there is some evidence for a deficit in spatial short-term memory, alternative interpretations of this evidence remain plausible. It is also difficult to rule out the possibility that these spatial short-term memory deficits spring from other, more general deficits. M.V. and G.P. are the only cases in which obvious deficits to cognitive processes besides spatial or visual short-term memory are not also evident.

Anatomical evidence from patient cases

For many of these cases, little precise anatomical information about the localization of the damage was provided. In cases where anatomical details were known, the damage was extensive. For M.V., we know that his stroke affected large sections of the frontal and parietal lobes in the right hemisphere, including Broadmann's areas (BA) 1, 2, 3, 4, 5, 6, 7, 8, 24, and 31. G.P.'s lesion was situated in the right frontal lobe, including BAs 4, 5, 6, 8, 9, 10, 11, 12, 24, 31, 32, and 33. E.L.D.'s damage was likewise described as “extensive”, but only delimited that the damage occurred to the right fronto-temporal region. E.P., who was believed to have impaired spatial short-term memory, also presented with right hemisphere temporal lobe damage (Luzzatti, et al., 1998). Ross's (1980) two cases both exhibited right hemisphere occipital damage, plus additional left occipital and right temporal lobe damage in one case. This extensive network of regions potentially affecting visual or spatial short-term memory poses further problems for interpreting the case findings: with such large extents of affected tissue in each case, it would admittedly be surprising to observe a very focused deficit. Furthermore, when taken together it is difficult to pinpoint a specific region where damage is likely to give rise to a specialized visual or spatial short-term memory deficit.

The most obvious commonality among the anatomical evidence provided by these patients is that the damage was usually localized to the right cerebral hemisphere. However, spatial short-term memory impairment can also co-occur with left hemisphere damage. De Renzi and Nichelli (1975) conducted a large-scale study including 125 hospitalized patients with either left- or right-hemispheric damage, testing verbal and spatial short-term memory in each patient. Participants completed a forward digit span test, digit span and picture span tests with pointing responses, and a spatial span test (also with pointing responses). Significant deficits in the verbal short-term memory tasks (i.e., forward digit span, digit and picture pointing span) in comparison with a control sample were exclusively observed in patients with left hemisphere damage. In contrast, individuals presenting with spatial span deficits came from both the left- and right-hemisphere patient groups.

Anatomical evidence from functional neuroimaging in healthy participants

Just as the neuropsychological case research does not afford decisive evidence for domain-specific short-term memory buffers, the functional neuroimaging literature likewise does not confirm the particular constellation of modules supposed by the multi-component working memory model of Baddeley (2012). To the contrary, there is growing consensus against the idea of any sort of specialized short-term memory stores based on neuroimaging evidence (ably summarized by D'Esposito & Postle, 2015). Though initial BOLD and PET evidence was interpreted as reflecting material-specific storage dissociations (e.g., Smith & Jonides, 1997), these distinctions have largely broken down as neuroimaging evidence accumulated. An illustrative example comes from research on domain-specific activation in the dorsal-lateral pre-frontal cortex (DLPFC), which was once believed to reflect separate stores for spatial and non-spatial contents. D'Esposito, Aguirre, Zarahn, Ballard, Shin, and Lease (1998) re-classified tasks meant to distinguish spatial from non-spatial memory activity in DLPFC by whether the tasks involved manipulation in addition to maintenance or not. A meta-analysis of these DLPFC activations showed that the maintenance-versus-manipulation classification produced a more obvious dissociation than the content-based classification, neatly questioning conventional wisdom about DLPFC function and demonstrating the need for deeper consideration about what processes the activations underlying any particular task reflect. More recent evidence tends to uphold the notion that DLPFC activity does not reflect storage (domain-specific or otherwise) per se, though evidence remains mixed (e.g., Feredoes, et al., 2011; Fried, Rushmore, Moss, Valero-Cabre, & Pascal-Leone, 2014; Nee, et al., 2013; Nee & D'Esposito, 2016) as to whether the manipulation and orienting functions that DLPFC activity seems to reflect are truly domain-general: possibly, fine-grained domain-specific sensitivity is present in DLPFC that would be challenging to measure precisely with current methods.

In any case however, the prevailing consensus suggests that the anatomical evidence supports "state-based" models of working memory, in which the notion of temporary storage is replaced by allocation of attention to activating long-term or sensory memories, or perhaps reconstructions of actions (D'Esposito & Postle, 2015). Neural activity in posterior sensory regions and in regions underlying motor activity that appears during short-term memory tasks is domain-specific. However, because this activity occurs in regions known to subserve functions other than memory storage, arguing that these activations constitute the workings of a specialized short-term memory buffer is clearly problematic. Two sorts of observations about this domain-specific activity make it difficult to equate this activity with the operation of a short-term memory buffer: 1) few if any distinct regions are activated during retention but not during encoding or retrieval, and 2) information can be successfully retained even if sustained neural activity cannot be associated with it. I shall describe evidence pertaining to each of these points next.

If there were structures specialized for holding information temporarily, then it should be possible to observe unique neural activation during temporary maintenance. These signals should differ from patterns observed during stimulus encoding, and should also differ from patterns observed when information is retrieved from long-term memory. Moreover, if there are distinct verbal and visual or spatial temporary stores, then the maintenance-related activity observed when holding verbal information should differ from that observed when holding visual or spatial information. As it happens, neural activity observed during maintenance often overlaps substantially with activation observed during encoding and responding. Furthermore, it is not clear that the activity that is unique to maintenance can be neatly divided by stimulus domain. For example, Majerus and colleagues (2010) compared the regions activated during verbal and visual memory tasks, manipulating whether participants were required to maintain only the identities of the stimuli, or also their presented order. Because maintaining their order depends heavily on remembering the specific, recent episodic context in which they were presented, activity related to the maintenance of order more plausibly reflects the localization of any temporary memory store. During both encoding and retrieval, Majerus et al. found that both tasks were served by a common fronto-parietal network. During maintenance, activation in this network decreased rapidly, and with little or no compensatory activity arising in other regions. Majerus et al. contrasted order with item tasks as well as verbal with visual stimuli to attempt to uncover selective activations that could reflect temporary memory stores. The regions specifically active during the verbal or visual tasks were the same regions active during perception of these materials; there were no unique regions specific to verbal or visual materials during maintenance. These domain-specific activations were more pronounced in item memory tasks than in order memory tasks, which is inconsistent with the notion of domain-specific temporary memory modules. Because the same regions supporting perception and encoding also support temporary maintenance, perhaps it is unnecessary to propose unique modules or mechanisms exclusively for domain-specific maintenance.

In other cases, posterior regions associated with storage might have been assumed to be associated with domain-specific storage without evidence from comparable control tasks using different content. Cowan et al. (2011) provided further evidence that activation specific to maintenance, particularly in a region that been previously associated with visual maintenance specifically, is not necessarily domain-specific. Participants were given visual stimuli, aurally-presented verbal stimuli, or both kinds of stimuli to remember on each trial. Cowan et al. searched for regions in which activations were sensitive to changes in memory load, defined by an increase in to-be-remembered visual array size from two colors to four colors or as an increase between maintaining two colors and maintaining two colors plus two digits. Activations acquired across two experiments honed in on a region of the left intraparietal sulcus that was sensitive to increases in memory load during the maintenance period. The same region appeared in previous searches for load-dependent areas during visual working memory tasks (Todd & Marois, 2004; 2005; Xu & Chun, 2006), and had previously been targeted as a potential basis for a visual working memory store.

Applied to working memory theory, assigning functions to BOLD activations is a non-trivial logical problem: it is not clear where and when distinctions between perception, attention, and maintenance should be assumed to arise. When we assume that a signal from a temporary store must arise during the trial's maintenance period, not earlier, we are assuming that encoding and maintenance happen in sequential steps, which is perhaps too strong a supposition. Without this assumption though, how can activations be ascribed specifically to attention or storage functions, both of which are assumed to be occurring in multi-component models of working memory? Lewis-Peacock, Drysdale, Oberauer and Postle (2012) applied multi-voxel pattern analysis to this problem, training a classifier to assign activation patterns to categorical descriptors consistent with those observed in a task involving phonological, semantic, or visual information. For the critical task, participants were given an item to remember from two of these three categories. During an initial retention period, one of the two items was cued for a recognition test. Immediately after this test, another cue was given, indicating either that the same item would be tested again (inducing participants to continue thinking of the same item), or cuing the other item for testing (inducing participants to retrieve the other item). Accuracies on these recognition tasks were at ceiling, indicating that participants had access to representations of both items. However, evidence from the pattern classifier suggested that only one of these representations was active at once during the retention period. On repeat-cue trials, the uncued representation dropped to the equivalent of a baseline control and never rose, but on switch-cue trials, each item became active after its cue and otherwise fell to baseline level. This pattern of results is inconsistent with the notion of dedicated short-term storage because apparently only the representation immediately required is represented in the activation patterns, even though the other representation can ultimately be retrieved. Temporary store models assume that stored information is represented by some active memory trace, which should be detectable even when unattended, but evidence for such representations was not detected in this case.

Taken together, these findings show that maintenance-related neural activation is difficult to disentangle from activation related to perception, encoding, or retrieval. Working memory theories are meant to explain the junction of these processes, but a coherent explanation may be possible without positing temporary storage modules of any kind. However, it remains possible that the patterns that would definitively support hypotheses of domain-specific temporary stores have not been observed because BOLD measurement techniques utilized in human research remain too insensitive. Courtney (2015; 2004) argues that the activations of the prefrontal cortex associated primarily with encoding and retrieval may yet encompass components that are specific to the maintenance of different classes of information, consistently with the evidence from single-cell recordings (reviewed by Goldman-Rakic, 1995). Despite this reasonable caution, it is nonetheless clear that the evidence currently available can be accommodated by working memory models that exclude temporary stores.

Conclusions from neuropsychological and neuroimaging evidence

A handful of documented patient cases portray deficits to visual or spatial short-term memory along with apparently intact verbal short-term memory. However, it is never clear that visual short-term memory is purely affected: deficits are typically accompanied by other more general impairments, which are either confirmed by comparison with controls or implied by lower-than-expected performance compared with the patients' intelligence test scores. This coincidence of impairments makes it difficult to conclude that these cases support the story of a specialized visual or spatial short-term memory system, because the possibility that visual or spatial short-term memory has been adversely impacted by a more general deficit cannot be excluded. Procedural differences between measures of memory for verbal, visual, and spatial information likewise make interpreting observed differences in memory spans with each of these materials awkward. Comparing across cases is complicated by differing operational definitions of “short-term memory”, which range from immediate recall to delays of many minutes, and encompass tasks that emphasize item recognition and serial order. Even within cases, it is difficult to pinpoint the precise nature of an observed deficit by comparing performance on tasks that likely differ in other respects apart from those aspects the researcher intended to manipulate. While these cases may be consistent with the idea of a specialized visual short-term memory system, they are just as consistent with propositions that maintaining memories in visual-spatial code is more dependent on general cognitive resources than maintaining verbal memoranda is.

The standard I set for finding a patient case that unequivocally pointed toward a visual-spatial short-term memory system was quite high: evidence of poor visual and/or spatial short-term memory in the absence of a deficit to verbal memory, visual or spatial long-term memory, or more general deficits in cognitive functioning. Given the strong likelihood of comorbidity of neuropsychological deficits, one may argue that this standard was impossible to observe. This highlights a pervasive problem with depending on neuropsychological case evidence for testing theories: acquiring this evidence is opportunistic, and having sufficient specificity for discriminating between similar hypotheses is likely impossible. The standard I chose is the minimum needed to unequivocally support hypotheses about specialized visual memory systems, regardless of whether it is likely or not. Even with its limits, the available neuropsychological patient evidence does clearly suggest that verbal and visual-spatial short-term memory rely to some degree on different resources. This much certainly ought to be accounted for in any coherent model of working memory, but accounting for it does not necessarily require the supposition of multiple specialized short-term memory stores. This blunt conclusion is perhaps the most that we can expect from neuropsychological evidence. This evidence therefore does not go far in distinguishing between working memory models that include a specialized visual short-term system and models that do not.

This assessment of neuropsychological cases of visual or spatial short-term memory deficits contrasts with characterizations given elsewhere (e.g., Alloway, et al., 2006; Baddeley, 2007; Cocchini, et al., 2002; Logie, 2011). Often, the strength of the selective patterns present in these patients is raised to support the inclusion of modular short-term systems in a multi-component working memory model despite ambiguous or contradictory evidence from experimental work. I contend that the case for specificity is frequently over-stated, and that in fact these cases can be accommodated by alternative perspectives. These cases should not be cited as definitive proof of specialized verbal and visual-spatial short-term memory systems, and should not greatly restrict the conclusions that may be drawn from experimental hypothesis testing.

Another notable problem for fairly comparing patients' visual short-term memory deficits with typical performance in healthy participants is that healthy participants are also likely to perform better on verbal than visual short-term memory tests. Healthy participants consistently perform better on verbal than visual short-term memory tests (e.g., C. Morey, R.

Morey, van der Reijden, & Holweg, 2013), on verbal than spatial short-term memory tests (e.g., Morey & Mall, 2012; Shah & Miyake, 1999; Vergauwe, et al., 2010), and with aural rather than visual presentation of verbal stimuli (e.g., Penney, 1989), at least for initial- and final-list items (Macken, Taylor, Kozlov, Hughes, & Jones, 2016). This typical pattern is one reason why the reversed patterns shown by K.F. (Warrington & Shallice, 1969) and P.V. (Basso, et al., 1982; Vallar & Baddeley, 1984), who are widely believed to have experienced selective auditory short-term memory deficits, were so striking and required explanation. However, because healthy participants are expected to perform more poorly on visual than verbal short-term memory tasks, we cannot rely on similar reversals when comparing patients with visual deficits with controls. Instead, one must show that difference between verbal and visual short-term memory is larger in patients than would be expected in controls, a subtler distinction that would require greater sensitivity to detect.

What interferes with the maintenance of visual memoranda?

It is clear that verbal short-term memory enjoys some degree of independence from other cognitive functions. This observation was one of the primary influences driving the emergence of the multiple-component working memory model (Baddeley & Hitch, 1974), and it has been confirmed with experimental methods designed to test whether maintenance of verbal lists is independent of encoding visual memoranda or storing visual memoranda. Verbal maintenance appears to be impervious to interference from both encoding and maintaining visual memories when short verbal lists are to-be-remembered. Morey and Mall (2012) report an example in which interleaved verbal and spatial lists are presented for maintenance, sometimes testing the short verbal list and sometimes the short spatial list. For 3-item lists, they observed no interference from spatial lists on verbal list memory, but did observe significant interference from verbal lists to spatial memory.

Comparable outcomes were likewise found when verbal lists and visual patterns were to be simultaneously remembered, indicating that cross-domain interference is not limited to remembering two serial lists with different contents. Morey et al. (2013) used a retro-cue paradigm to isolate maintenance processes. They presented participants with lists of digits and patterns of colored squares, manipulating the order of presentation of each stimulus set and also whether one set was retro-cued for eventual testing. When a set was cued, participants could focus during the 3-second retention interval on trying to remember the to-be-tested set. Morey et al. compared capacity estimates with and without retro-cues separately for verbal and visual memoranda. For visual memoranda, capacity estimates were lower without retro-cues than with a retro-cue, indicating that interference from the verbal memoranda occurred during the maintenance interval, in addition to whatever interference already occurred from encoding two stimulus sets. However for verbal memoranda, no discernible effects specific to maintaining the visual arrays appeared. Morey and Miron (2016) replicated this finding using concurrently-presented verbal and spatial sequences. Though interference attributable to encoding the other sequence occurred for both verbal and spatial tasks, interference due to maintaining another list only occurred for the spatial task.

These studies, designed to isolate short-term maintenance processes and test for interference specific to maintenance (to the degree that such isolation is possible), clearly indicate that visual information is more susceptible to general interference during maintenance than verbal information is. However, they do not clearly test the essential hypothesis that some small amount of visual material may be maintained without cross-domain interference. Morey and Miron (2016) tested memory for 5-item sequences, which may exceed the capability of a specialized visual memory buffer. Morey et al.'s (2013) studies included visual arrays of as few as 2 items, but they never analyzed performance with small array sizes in isolation. If a specialized visual short-term memory system capable of holding a small set of information were in operation, then possibly maintaining small arrays of 2 or 3 items occurred without substantial interference from encoding or maintaining a verbal list. I re-analyzed a subset of Morey et al.'s published data set to test this hypothesis. The data and analysis scripts are publicly available on Open Science Framework (https://osf.io/f5ypx/).

Re-analysis of interference to the smallest visual arrays of Morey, et al. (2013)

In Morey et al.'s (2013) analyses, capacity estimates were calculated by pooling across large and small visual array sizes. However, novel analyses also show that even when only the small array sizes with only 2 or 3 colors to be remembered are considered, interference from simultaneously maintaining verbal information or from encoding a verbal list is apparent[1]. I ran a 2 x 2 x 2 Bayesian ANOVA (Morey & Rouder, 2015; Rouder, Morey, Speckman, & Province, 2012) on differences between single-task and dual-task conditions using data from Experiments 1a, 1b, 2a, and 2b of Morey et al., with verbal list length (3 or 6), array presentation order (before or after the verbal list), and retro-cue condition (visual array cued or uninformative) as factors. The winning model included main effects of all three factors (*BF* more than 1 million). The main effect of retro-cue (M_{Cue}=0.05, $M_{Uniformative}$=0.10, inclusion favored more than 150:1) indicated that interference costs were higher when verbal lists and visual arrays were simultaneously maintained. The main effect of presentation order ($M_{BeforeVerbal}$=0.12, $M_{AfterVerbal}$=0.04, inclusion favored more than 700,000:1) indicates that encoding the verbal list while maintaining the visual array also took a toll. The main effect of verbal list length ($M_{Length=3}$=0.06, $M_{Length=6}$=0.10, inclusion favored more than 25:1)

1 I first ran a 4-way ANOVA including an additional factor distinguishing between 2- and 3-item visual arrays. Performance as a function of the other factors was similar for both array sizes, so I collapsed across array size for simplicity.

indicates that dual-task costs rose as verbal list length increased. Figure 1 show that in every factor combination, mean costs exceeded zero.

To confirm that even very small amounts of visual information suffer a dual-task cost from very small amounts of non-visual information, I ran another Bayesian ANOVA on arcsine-square-root-transformed proportions correct for arrays of only 2-items under baseline single-task conditions and with verbal lists of only 3 items. Presentation order and retro-cue condition were again included as factors. The best model included an effect of presentation order (BF=13.93, ± 1.28%). This main effect implies a dual-task effect because the presentation order factor differentiates between single-task trials (which have no meaningful order, M=0.91), dual-task trials in which the visual array was presented after the verbal list (M=0.89), and dual-task trials in which the visual array was presented before the verbal list (M=0.83). The direction of this effect suggests that even encoding a 3-item verbal list interferes with maintaining a visual array of even 2 items.

Combined with published evidence from Morey and Mall (2012), which showed that even spatial lists of 3 positions were impaired during a concurrent verbal memory task, these novel analyses of Morey et al.'s data (2013) focusing on only the smallest visual array sizes confirm that not even small amounts of visual information can be held without measurable interference from non-visual sources. This contrasts with comparable analyses on verbal memory, which suggest that short verbal lists are resistant to interference from non-verbal sources, at least under some circumstances (Morey & Mall, 2012; Morey, et al., 2013). These data cast doubt on whether visual memoranda meet the two basic thresholds I suggested above for assuming storage modularity, namely that: 1) some information may be maintained without discernible dual-task cost, and 2) when there is a cost, it is not attributable to interference during maintenance. Even though domain-specific interference is consistently greater than domain-general interference, these data reveal patterns that are inconsistent with the idea that even two simple visual items may be maintained cost-free by a specialized short-term storage module.

Meta-analysis

To thoroughly assess whether the literature more broadly considered requires that we assume a specialized visual short-term store, I brought as much data as I could find to this question through meta-analysis. To learn what kinds of tasks interfere with maintenance of visual information, I searched the literature for any study in which visual memory was measured, and in which memory performance with no secondary task and memory performance with some secondary task was reported. I coded several aspects of the secondary tasks in order to later sort them by these potentially relevant factors. The data frame and analysis script are available at https://osf.io/dvh2c/.

Method

I began searching this literature by querying a conjunction of two sets of search terms, one targeting visual short-term or working memory (visual short-term memory, visual working memory, visuo-spatial sketchpad, visuo-spatial scratchpad, visuospatial sketchpad, visuospatial scratchpad) and another to detect papers using dual-task methods (dual-task load, dual-task interference, multi-task, secondary task, concurrent task, distractor) in Web of Science. First, I searched restricting to results that included at least one term from both of these sets in the title of the paper, which produced 12 papers. I broadened this search to allow one or both of these search terms to appear in the topic of the paper, which produced as many as 2,954 results. Perusing the abstracts in the first few pages of this fully inclusive search result convinced me that most of the papers were unlikely to meet my additional inclusion criteria. I therefore settled on a combination of searching for any of the visual short-term memory synonyms in the title and any of the dual-task synonyms in the topic in order to generate a more inclusive but manageable set. After excluding papers published in languages other than English, in disciplines other than psychology, and in formats other than peer-reviewed articles, this set included 133 results.

I also looked for results meeting the same criteria on www.psychfiledrawer.org to counteract publication bias, but no additional data meeting these criteria had been deposited there. The risk for this meta-analysis to be influenced by publication bias is low because the descriptive outcome measures I used for comparison would have been reported in the context of other analyses, and need not themselves have been statistically significant to be published. In some cases, the original authors were testing for the presence of an interaction and did not report simple tests of whether the visual memory measure was significantly worse in the dual-task condition. In other cases, the visual memory measure I used was a secondary task, not the primary focus of the paper. Compared with a meta-analysis focusing on a finding (or not) of a specific outcome, the broad method I employed had the potential to catch small or contrary effects evident in data reported alongside other, statistically-significant effects.

I read each of these 133 abstracts, following up with the paper as necessary, to check whether the paper met my other inclusion criteria. To be useful, each paper should 1) measure visual memory performance via accuracy, excluding memory for visually-presented verbal material; 2) include a report of some measure of visual memory without a secondary task plus the same measure with a secondary task; 3) test visual memory in a sample of healthy adult participants. Many of the papers did not meet these criteria, and various others cited by one of these 133 papers (but not appearing in this list itself) did meet these criteria. Whenever I found a paper that met these criteria, even if not via my formal search, I added it to my analysis. In total, data from 90 papers are included in the data frame publicly available on Open Science Framework, and the 74 that were included in the analyses are marked (*) in the references. Table 3 lists the papers, showing which papers contributed data to which analyses (by Figures). I do not claim to have found each and every published instance of a visual working memory task with and without a dual-task load using these search methods. Many papers focusing on other elements of visual cognition, but including memory measures, likely eluded my search. Similarly, papers focusing on memory more generally but measuring visual memory specifically might have slipped through. By the inclusion of multi-component model terminology and the criterion that the title must include some synonym for "visual" working memory, my formal search was, if anything, biased toward papers arguing for distinctions between visual and other kinds of memory. In general, my guiding principle was to err on the side of inclusion.

For each paper, I coded the following attributes for potential analysis: 1) what the visual memoranda were (e.g., spatial locations, color-shape arrays, orientations, patterns, etc.), 2) the visual memory task requirements (remember sequences, remember patterns, remember binding, n-back, etc.), 3) whether binding was required (either item-in-position, or intrinsic feature binding), 4) the number of to-be-remembered elements, 5) what the secondary stimulus was (e.g., words, tones, visual noise, visual search array, etc.), and 6) the domain of the secondary stimulus (e.g., verbal, auditory, visual), 7) whether any non-repetitive response to the secondary task was expected, and 8) the length of time the visual memoranda were to be maintained. The data frame also includes the identity of the dependent variable (e.g., proportions correct, spans, capacity estimates, etc.), the number of participants and trials sampled, means and variability around the dependent measure of visual memory with and without the secondary task, the most relevant reported test statistics, and the pages on which the test statistics were found. I generally chose not to collapse across other factors manipulated in the original paper, unless the data in the original paper were only reported in that manner. For instance, if a single paper reported the same visual memory task varying the number of to-be-remembered items, or the length of a retention interval, I considered each dual-task and single-task mean reported at each level of those independent variables to be separate data points. For some papers, the descriptive values were presented by unanalyzed factors (such as serial position, or separate reports of means of same and change trials in change recognition tasks). In these cases, I collapsed across the unanalyzed factor. Coding at this level of specificity allowed for the selective exclusion of individual data points that did not meet certain criteria, allowing data points from as many separate papers as possible to remain in the most restrictive analyses I carried out.

My aim was to evaluate the sizes of the effects of various secondary tasks, rather than to confirm the presence or absence of statistically-significant effects[2]. I recorded condition means, standard deviations, and sample sizes where these were reported, in the dependent variable reported. Before computing effect sizes, it was necessary to recode some dependent variables (e.g., percent or proportions errors) for consistency, so that subtracting the dual-task mean from the single-task mean would consistently indicate a dual-task cost. I did this in my publicly available analysis script rather than recoding the values recorded in the data frame. Because the appropriate *t*-statistic or correlation was not usually reported, I computed Cohen's d_{av} (as recommended by Lakens, 2013) on the differences between the single- and dual-task means. Standard deviations for computing d_{av} were either taken from the paper, or

2 In many cases, simple main effect I would want to compare was part of a more complex experimental design, and the particular comparison of interest was not reported in the original manuscript. Choosing to evaluate effect sizes therefore allowed for the inclusion of more data.

if some other measure of variability was reported, I used it to estimate the standard deviations. If no measure of variability was reported, I inserted the data set's mean standard deviation for all the other the data of the same sort of dependent variable (e.g., span scores, proportion correct, percent correct) to avoid having to exclude an otherwise valid data point. Following the advice of Lakens (2013), I applied the Hedges's G correction, which reduces bias introduced by differences in sample sizes, to all the effect size estimates.

To gage subjectivity of the coding and catch accidental errors, I enlisted a second rater to reproduce my coding on a subset (N=69 papers, 744 observations) of the papers. I provided definitions of the moderators to be rated. The raters did not communicate further about the coding until the second rater finished the task. Reliability was always statistically significant and quite strongly positive (k^2 from 0.51 to 0.80). I analyzed discrepancies between raters to learn whether disagreements were systematic, and to flag and correct errors, focusing most on those related to assigning an observation to a distractor category. Most discrepancies were due somewhat different interpretations of the moderator definitions. Discrepancies in coding distractor domain (k^2=0.63) occurred because one rater considered any secondary task presented aurally as “auditory”, whereas another defined “verbal” tasks as those focusing on verbal content regardless of presentation modality. I resolved the discrepancies according to the latter definition. Discrepancies in whether a distractor task required a considered response (k^2=0.51) occurred because one rater 1) did not consider a secondary memory task as requiring a response, and 2) coded this factor as “no” if articulatory suppression was used alongside another secondary task, which occurs frequently in visual memory research. I resolved these discrepancies so that articulatory suppression was ignored if there was another secondary task, and such that secondary task that required maintaining information was listed as requiring a response. I re-examined each discrepancy against the original paper before resolving the discrepancies. In reconsidering codings following examining these inter-rater discrepancies and cross-checking across multiple moderator variables to ensure that their codes were always internally consistent (e.g., that single-feature stimuli were never recorded as requiring binding, or that distracting tasks that required watching or listening without replying were consistently labeled as "perception"), I modified 25 of the original rater's decisions.

Not all of the 1087 observations coded were suitable for analysis. I excluded the 8 data points provided by Morris (1987) because it was unclear how the dependent variable was calculated. I decided to exclude the 23 instances where the dual-task factor was manipulated between-subjects because it is unclear how such a cost could be interpreted. A few papers introduced a secondary task which used a comparatively rare stimulus modality (e.g., time perception, haptic interference). I excluded these 27 data points because I deemed it unfair to compare means based on so little data with means from the auditory, verbal, and visual categories, which included hundreds of data points each. I excluded 34 additional data points that came from paradigms in which the auditory secondary task required judgment of the spatial location of a sound, because this could be considered spatial interference. Though I included some studies with varying levels of dual-task difficulty but no true control in my data set, I excluded the 103 data points coming from studies without a pure single-task control condition. This left 862 observations for analysis.

Results

Though the intent of many studies has been to test whether within-domain visual-spatial distractors interfere more with visual-spatial memoranda than non-visual ones, mean differences can nevertheless be used to ascertain how large an effect within- versus cross-domain distractors typically have on visual-spatial memoranda. I begin by reporting the most inclusive picture of effect size differences between visual-spatial memory with and without secondary tasks, grouping secondary tasks by the domain of material participants were required to remember or process. I gradually filtered the data included in the meta-analysis to hone in on stronger ways of discerning what kinds of materials interfere with maintaining visuo-spatial memoranda, restricting the analysis to studies with maintenance intervals of at least 1 second (N=748) in order to ensure that maintenance beyond sensory memory was required, and finally restricting the analysis to instances in which no more than three visual or spatial memoranda were to be remembered (N=354), in order to see whether small amounts of information might be more impervious to interference.

Figure 2a shows distributions of effect sizes for differences between single task visual memory performance and visual memory performance during some secondary task which required the storage or processing of auditory, verbal, or visual-spatial materials. Variation across included studies due to heterogeneity (I^2) was 27.86%. Secondary tasks in the auditory distractor category included memory or categorization tasks of auditory stimuli such as tones or birdcalls, or simply listening to non-verbal sounds. Verbal distractor tasks included backwards counting, articulatory suppression, listening to verbal input, verbal memory, and semantic categorization. Visual-spatial distractors included visual search or visual categorization, presentation of visual noise, spatial tapping, and visual memory tasks. For each of these, I computed the average effect size (weighted by sample size) and 95% credible intervals around this mean, which may be interpreted as the interval with a 95% chance of containing the true effect size (Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2016) according to the data sampled. No matter the domain of the secondary task, the weighted average effect size was substantially higher than zero ($M_{Auditory}$=0.45 ± 0.07 , M_{Verbal}=0.66 ± 0.08, M_{Visual}=0.67 ± 0.07). The 95% credible intervals (plotted in each panel of Figure 2), never included 0.

To further ensure that we only considering non-sensory memory, I estimated weighted means and credible intervals for the subset of the data that required visual memoranda to be retained for at least 1000 ms. These distributions are shown in Figure 2b. Effect sizes remain substantially larger than 0 regardless of the domain of the secondary task ($M_{Auditory}$=0.45 ± 0.07, M_{Verbal}=0.68 ± 0.09, M_{Visual}=0.69 ± 0.07), and the 95% credible intervals never included 0. To test whether cross-domain interference is observed even when small amounts of visual information are to-be-remembered, I filtered the data frame again, excluding any instances where more than 3 visual items were to-be-remembered. Effect sizes remained well above 0 for each domain category ($M_{Auditory}$=0.41 ± 0.09 , M_{Verbal}=0.59 ± 0.12, M_{Visual}=0.71 ± 0.09), with 95% credible intervals always excluding 0. These distributions are shown in Figure 2c.

Even with small visual memory loads, there is no reason to believe that visual information can be maintained without a cross-domain interference cost based on these patterns, as seems to be the case with verbal memoranda. Regardless of the domain of distractors, average effect sizes of an interfering task on visual memory were moderate to robust according to common conventions, and the 95% credible regions around the average effect sizes never approached zero. Figures 2a, 2b, and 2c furthermore give little reason to believe that the domain of the interfering material changes the size of interference effects much. Though auditory distractors appear to cause smaller interference than visual ones, 95% credible regions on effect sizes of verbal distractors (which might have been presented aurally or visually) consistently overlap with those of visual distractors. Other systematically manipulated factors have larger differential effects on visual memory performance. An analysis of the demand of the secondary task is shown in Figure 3. When the secondary task required memory or the selection of a non-repetitive choice response, average effect sizes were consistently high regardless of domain, and the overlapping 95% credible intervals suggest that there is no reason to suppose that a cognitively-demanding visual task provokes greater interference than a demanding auditory or verbal task. However, when the secondary task involved only passive perception or repetitive action, effect sizes were much smaller, except when the distractor task materials were visual. With visual materials, the 95% credible intervals overlapped regardless of secondary task demand. It therefore appears that the cognitive load of the secondary task has a much larger impact on visual memory than sensory or domain overlap does.

General Discussion

I investigated the available evidence supporting the prevalent idea of a specialized visual short-term memory system. The theoretical development of the multi-component working memory model (Baddeley, 2012; Logie, 2011) was influenced by evidence suggesting that verbal short-term memory could be selectively impaired by brain damage and empirical dual-task research showing that verbal short-term memory loads provoke little, if any, dual-task interference (Baddeley & Hitch, 1974), except to other verbal memory tasks (e.g., Cocchini, et al., 2002; Logie, Zucco, & Baddeley, 1990). Though the equivalent pattern has been assumed for visual short-term memory, the available evidence looks quite different. Neuropsychological patients believed to evince a selective deficit for visual or spatial short-term memory all present with more extensive patterns of dysfunction. Dual-task methods likewise do not provide strong evidence supporting a specifically visual short-term memory component. The pattern of evidence clearly suggests that many kinds of cognitive tasks, not only those with domain-specific overlap, interfere with maintenance of visual memoranda. Judgments about such disparate stimuli as spoken words or tones consistently interfere with visual memoranda. This evidence does not require models of working memory to posit a specialized resource for briefly maintaining only visual short-term memories.

Previously, in some instances where visual or spatial memory tasks have not mirrored the selective interference observed in verbal tasks, authors supposed that verbal recoding of the visual or spatial stimuli was the reason (see, for example, Shah & Miyake, 1996). Under some circumstances, memory of visual stimuli may be supplemented or perhaps replaced by a verbal label capturing the information (Brandimonte, et al., 1992; Schooler & Engstler-Schooler, 1990). However, reasoning that visual memoranda are susceptible to general interference solely because participants engage in verbal coding is unsatisfying. While evidence suggests that visual information may be encoded verbally under some circumstances, this is no way suggests that such recoding always occurs. Studies attempting to show effects of verbalization on visual memory use materials specifically shown to be amenable to verbal labeling (e.g., Brandimonte, Hitch, & Bishop, 1992; Brown, Forbes, & McConnell, 2006; Brown & Wesley, 2013) and tend to deploy longer stimulus exposures than used in comparable tasks to better facilitate the generation of a verbal label (e.g., Mate, Allen, & Baques, 2012). Under these circumstances, use of verbalization is demonstrated by showing that concurrent articulatory suppression impairs task performance. However, with faster presentation times and abstract stimuli that do not easily lend themselves to verbal labeling, articulatory suppression does not impair visual memory (Luria, Sessa, Gotler, Jolicoeur, & Dell'Acqua, 2010; Morey & Cowan, 2004; 2005; Sense, C. Morey, Heathcote, Prince, & R. Morey, 2016). The abstract visual stimuli now commonly used to measure visual short-term memory cannot be quickly reduced to a concise verbal label that reliably distinguishes the salient aspects of one visual stimulus from another (Souza & Skora, 2017). Furthermore, the very idea that verbalization could be the primary strategy for remembering visual images would seem to belie the hypothesis that we have access to a mental resource specifically for maintaining visual memories. While verbal labeling may have some impact on remembering visual information (as gesturing or visualization may likewise have some impact on verbal memory), the evidence I have evaluated here cannot be summarily dismissed on the grounds that visual memory tasks are too dependent on verbal strategy use without completely undermining the study of visual short-term memory, and indeed, the very idea of a separate visual short-term memory system.

No current working memory model manages to satisfactorily explain why verbal and visual memoranda differ in their vulnerability to general interference. I shall describe competing models of working memory (or models of memory that may be applied to short-term memory phenomena) and consider how each theory might accommodate asymmetry between verbal and visual-spatial mnemonic representations.

Theoretical approaches to domain-specificity in working memory

When assumptions about parallel operations between verbal and visual memory are set aside rather than taken for granted, it becomes clear that domain-specific visual stores or rehearsal modules are not necessary for explaining existing data. The strong assumption of domain-specific stores was based largely on the supposed existence of patients who had selectively lost access to either auditory, visual, or spatial short-term memory. Evidence based on the patients with apparent auditory short-term memory loss has been skeptically re-considered, and is not universally believed to reflect a selective short-term memory deficit (e.g., Caplan, Waters, & Howard, 2012). The evidence from patients who experience difficulties with visual or spatial materials is even less consistent with the idea of a selective short-term memory deficit, and likewise deserves skepticism. De-emphasizing the evidence afforded by these patient cases should lead us to reconsider the objections to modular visual or spatial short-term storage raised by Phillips and Christie (1977b), which were perhaps abandoned too hastily. Phillips and Christie did not take the strong position that visual information is *not* maintained in a distinct module; instead, they argued that the available evidence was insufficient to decide between a system in which a general resource is needed to act on some distinct visual memory module and a system in which the general resource is responsible for maintaining visual representations. As the multi-component model grew more popular, the separate short-term memory stores hypothesis became the standard view even though remaining skeptical towards the notion of a visual-spatial short-term memory store would have been just as consistent with the available evidence. I argue that there is now sufficient evidence to instead adopt the more parsimonious view that there is no "special purpose visualizer", as Phillips and Christie put it. Pending new evidence that actually mandates both specific visual memory stores and general resources for adequate explanation, we should proceed with modeling working memory based on the overwhelming empirical evidence that visual short-term memory relies primarily on domain-general cognitive resources.

At the very least, frameworks retaining visual-spatial short-term stores should be re-specified so that the fragility of visual information in comparison with verbal information is clearly accounted for. Within the dominant model of working memory, the multi-component model (Baddeley, 2012), this could mean allowing the general-purpose episodic buffer a greater role in maintaining visual-spatial information than currently assumed. This could range from the complete removal of a specific visual-spatial short-term memory component, with all its operations subsumed by the domain-general episodic buffer, or perhaps a restricted role for a specific visual short-term memory component. Given the evidence summarized here, justifying the inclusion of both the domain-general episodic buffer and the specialized visual short-term memory store will be challenging. In summarizing the available neuropsychological case literature and the empirical literature on dual-task costs on visual memory, I observed none of the strong benchmarks expected if short-term visual memories are maintained in a specialized system. Possibly, there exist restricted circumstances in which a specialized visual store can operate. These restrictions need to be clearly delineated and differentiated from the operations of other presumed working memory components. The properties and capabilities of any specialized visual short-term memory store should no longer be assumed analogous to a specialized verbal short-term memory storage system.

However, assuming both domain-specific and domain-general short-term memory storage within working memory may not be necessary at all. Some models of working memory do not emphasize roles of domain-specific short-term memory stores. Embedded process models (Cowan, 2005; Oberauer, 2013) neither explicitly disavow nor incorporate domain-specific stores. Embedded process models propose that a subset of the sensory memories or long-term knowledge occupies a state of especially heightened activation, referred to as the *focus of attention*. While in this heightened state, activated information is less susceptible to interference or gradual decay (Ricker & Cowan, 2014). However, very little information can occupy the attentional focus at any given moment. Various models estimate this limit at about 4 items or chunks of information (Cowan, 2001; Gilchrist & Cowan, 2011) or even only 1 item or chunk (Basak & Verhaeghen, 2011; Oberauer, 2013). Information that is not in the focus of attention varies in its level of activation. More highly-activated items may be more easily retrieved and promoted to the focus of attention.

Cue-based retrieval models (e.g., Nairne, 2002; Unsworth & Engle, 2007) also focus on explaining immediate memory by considering accessibility of information. Contrary to the notion that some information is held in short-term memory buffers that are subject to passive decay, it has been shown that recovering an immediate memory is largely dependent on how the memory is elicited, just as recovering a more distant memory is. If temporarily activated short-term memories fade with time, then eventually they should be unrecoverable regardless of the nature of the cue used to elicit them, but cue-dependent variability in retrieval success is consistently observed (e.g., Tehan & Humphreys, 1996). Cue-based retrieval models vary in whether memory is considered to be unitary or not. Unsworth and Engle's model lies between the embedded process models and Nairne's unitary cue-based memory retrieval conception in that Unsworth and Engle argue for dual-component framework, setting *primary* memory apart from *secondary* memory much as the embedded process models distinguish the contents of the focus of attention from other memories. Whichever term is applied, *attention/primary memory* is characterized as a privileged state in which information is protected from interference, but is not proposed to be divisible according to the sensory domain or code of the memories represented.

Though these models do not assume domain-specific short-term memory stores, we should not necessarily assume that these models predict that verbal and visual-spatial information is treated equivalently. In focusing on accessibility of information, embedded process models and cue-based retrieval models remain quite flexible about how assumptions about domain-specificity of memories might be implemented. Embedded process models make no specific claim about the construction of the systems contributing to activated memory, and thus presumably depend on resolution of other disagreements about how sensory memories and long-term knowledge are immediately represented for a full description. One solution allows for domain-specific stores to co-exist alongside embedded processes, by subsuming them within activated memory (e.g., Cowan, 1988). This solution unparsimoniously allows for any possible combination of specialized short-term memory components. If neither empirical nor neuropsychological evidence demands these short-term memory buffers, then we need not advocate for this comprehensive solution. Instead, both unitary and dual-component memory models may suppose that domain-specific limitations are inherited from perception, sensory memory, or long-term knowledge, or some combination of these. Observed asymmetries in robustness of verbal and non-verbal information must be supported by assumptions about the peripheral sensory and long-term memory systems that underlie embedded process or cue-based retrieval models.

Some models of working memory besides the multi-component model (Baddeley, 2012) incorporate domain-specificity into their frameworks and predictions. I shall describe two accounts of working memory phenomena that incorporate domain-specificity in different ways: the most recent version of the Time-based Resource Sharing (TBRS) model (Barrouillet & Camos, 2015) and perceptual-gestural embodied accounts (e.g., Jones, et al., 2006; Macken, Taylor, & Jones, 2015). Both of these accounts could handle evidence showing that visual memoranda are more susceptible to general interference than verbal memoranda, but do so by making very different assumptions.

Time-based Resource Sharing Model (2015). The latest iteration of the time-based resource sharing model (Barrouillet & Camos, 2015) inherits many ideas from the traditional multi-component models of Baddeley (1986; 2012). In Barrouillet and Camos's conception, the heart of a working memory system is a linked representation and production system in which the same limited cognitive resource is devoted to holding representations and ensuring they remain activated. This central system, which Barrouillet and Camos specify as domain-general, is fed by a collection of specialized peripheral resources. The presumed nature of these resources is inspired by previous working memory models. From the ACT-R model of cognition (Anderson, et al., 2004), TBRS inherits modules for temporary maintenance of declarative long-term memories, current task goals, and motor actions. From the classic multi-component model (Baddeley, 1986), TBRS inherits a visual-spatial buffer (akin to the multi-component model's visual cache) and a phonological buffer. Consistently with Baddeley and colleagues, Barrouillet and Camos characterize these peripheral systems as *passive*: information may be represented in these modules, but until it is selected for representation in the central working memory system (which Barrouillet and Camos characterize as an episodic buffer refreshed by a production system, which in combination form an *executive loop*), representations maintained in the peripheral stores fade as time passes. Information that is not selected and refreshed by the central system will eventually decay past the possibility of accurate recovery.

The sole exception to this cycle of refreshing and decay by Barrouillet and Camos's (2015) central cognitive system is for rote rehearsal of verbal information. The contents of the passive, peripheral phonological buffer alone can be re-activated through articulatory rehearsal, which is accomplished independently of the central system. This exception is based on empirical findings that keeping verbal information active does not necessarily interfere with maintenance of other kinds of information (Camos, Lagner, & Barrouillet, 2009; Camos, Mora, & Oberauer, 2011), and is likewise consistent with an abundance of evidence that maintaining verbal information suffers little (Shah & Miyake, 1999; Vergauwe, Barrouillet, & Camos, 2010) or not at all (Morey et al., 2013) from concurrently storing or processing visual information, while a variety of materials and tasks provoke interference to visual memories.

This latest iteration of TBRS is heavily inspired by the classic multi-component model (Baddeley, 2000), adopting the pieces for which there is strongest consensus and jettisoning the pieces with the least support, most notably specialized visual or spatial rehearsal mechanisms. This selectivity enables TBRS to better account for the non-selective interference with visual memories that I have described. However, like the classic multi-component model, thoroughly testing this version of TBRS will be difficult: it will be challenging to devise experimental tests that convincingly isolate the components of the system meant to be under scrutiny, and to potentially falsify any single component. This is especially true given the flexibility with which information may be encoded: verbal information might be maintained via visual imagery (e.g., Brandimonte, Hitch, & Bishop, 1992; Logie, Della Sala, Wynn, & Baddeley, 2000; Postle, et al., 2006) and visual information might be encoded via verbal labels (e.g., Schooler & Engstler-Schooler, 1990). Support for this constellation of components therefore must arise from the consistency of a large body of evidence. Though many might say this consistent body of evidence is already in place, in this paper I have shown that there is reason to doubt whether the data supporting our conventional wisdom really discriminates between similar theoretical possibilities.

Although TBRS (Barrouillet & Camos, 2015) specifically includes components that support the prediction that verbal information is more resistant to general interference than visual information, TBRS does not perfectly account for the differential interference patterns observed by Morey et al. (2013). Though it is clear that verbal information should resist interference better than visual information, TBRS does not predict any interference between a serial verbal memory task, which could rely on its specialized sub-system, and a non-verbal memory task, which could rely on the domain-general executive loop. According to TBRS, overloading the verbal rehearsal component during a visual memory task should provoke some dual-task interference. Excess verbal information would require the executive loop activation, causing competition between the verbal and visual memoranda. However, in this scenario, verbal task performance would also suffer. One potential factor to re-consider is evidence that even automatic verbal rehearsal may include an attention-demanding planning phase (Naveh-Benjamin & Jonides, 1984). Invoking the idea that the initiation of verbal rehearsal requires general resources might partially explain why verbal memories interfere with visual memories while remaining resistant to general interference themselves.

Perceptual-gestural embodied accounts. Embodied accounts of short-term memory (e.g., Glenberg, 1997; Macken, Taylor, & Jones, 2015) attempt to explain memory phenomena in reference only to well-established perceptual and motor systems. An account of working memory that resorts only to perceptual, motor, and long-term memory systems rather than additionally proposing one or more distinct short-term memory systems would have the advantage of more parsimoniously accounting for the data. Whether these attempts have succeeded or not is a matter of debate, and one that largely hinges upon how apparent selective short-term memory deficits in patients are best explained: If these deficits were definitively shown to implicate hypothetical short-term stores, then explaining short-term memory phenomena without recourse to specialized stores would not be so plausible. However, whether the patient evidence really demands the supposition of short-term storage modules remains dubious (Caplan, et al., 2012), making attempts to do without short-term memory stores a viable, parsimonious approach. In short-term memory, most of the available experimental evidence and argument on these points pertains to verbal memory storage. I will recount these arguments briefly before considering the unique predictions about visual short-term memory phenomena that seem to arise naturally from the embodied perspective.

The strongest experimental case for explaining short-term memory phenomena without positing a short-term memory store comes from consideration of the predictions about verbal serial recall arising from the multi-component model. According to the multi-component working memory model, verbal information is held in the *phonological store*, where its phonological characteristics are preserved, giving rise to interference based on phonological similarity and temporal duration. There are two routes to entry into the phonological store: aurally-presented items are encoded directly into the phonological store, whereas visually-presented items get access to the phonological store via an additional process, articulatory re-coding. Crucially though, as long as aurally- and visually-presented items both gain access to this phonological store, both should be subject to phonological similarity effects, and these effects should appear throughout the serial position functions because they act upon all of the information held in the phonological store. Engaging in articulatory suppression disrupts the conversion of visually-presented verbal materials to phonological code, and should therefore reduce any effect of phonological similarity throughout the list. Supporting the multi-component model's buffer-plus-articulation idea, concurrent articulation reliably reduces the impact of phonological similarity on visually-presented lists (Baddeley & Larsen, 2007; Baddeley, Lewis, & Vallar, 1984; Jones, Macken, & Nichols, 2004). However, the locus of this effect within an ordered list is less clear; sometimes this impact appears throughout the list, but sometimes striking interactions emerge in which aurally-presented materials show a clear recency effect regardless of whether they are phonologically similar or dissimilar or whether suppression is imposed, while visually-presented materials do not (Jones, et al., 2004). Additionally, the phonological similarity effects reliably observed at list-final positions are disrupted by purely acoustic factors such as the addition of suffixes and prefixes (Jones, et al., 2004; Jones, Hughes, & Macken, 2007), suggesting that if anything, an acoustic, rather than a phonological, representation is maintained. These observations cast doubt on the buffer-plus-articulation notion, raising the possibility that the phenomena may be explained without assuming any buffer at all, and instead supposing that early-list items suffer more from phonological similarity than late ones because they are most sensitive to interference that arises while planning a spoken response. Final-list items may be impaired by a suffix not because they are maintained in a domain-specific buffer that the suffix automatically accesses, but because auditory perception is biased toward grouping adjacent sounds together, even if these items are not part of the intended response set. Encoding the suffix along with the end-of-list items results in confusions about which item was to-be-ignored and which was to-be-remembered, increasing errors.

In response, Baddeley and Larsen (2007) invoke the complexity of the multi-component working memory model and the apparent impossibility of truly isolating its components: they discuss the multiple possibilities for domain-specific and domain-general representation and rehearsal, which might be strategically adopted or abandoned based on many circumstantial factors. They fall back on the evidence provided by neuropsychological cases in which aural-verbal short-term storage appears to be uniquely impaired (e.g., Basso, et al., 1982; Warrington & Shallice, 1969), strongly suggesting that aural-verbal short-term storage is an independently manipulatable cognitive mechanism. According to Baddeley and Larsen, even when experimental hypothesis tests fail to support the multi-component model, we still must credit it on account of the strength of the neuropsychological case data. This makes interpreting these rare data profoundly important, because interpretation limits how we can deploy our most power scientific tool, experimental falsification.

In fact though, the same neuropsychological case data may be interpreted without recourse to domain-specific stores. Caplan, Waters, and Howard (2012) re-examined cases of auditory short-term memory deficits, and argued that the patient evidence is not consistent with the phonological store and articulatory loop components as described by the multi-component working memory theory. The cases described most in-depth, those of P.V. (Vallar & Baddeley, 1984) and K.F. (Warrington & Shallice, 1972), are not necessarily consistent with assumptions about an impaired or absent phonological store: in both cases, effects arising from maintenance in the phonological store, such as phonological similarity effects, remain present with aural presentation. These inconsistencies, like those with healthy participants (Baddeley, 2000), are dealt with by the inelegant supposition that use of the phonological store is strategically abandoned whenever phonological storage becomes difficult (Shallice & Vallar, 1990), a proposition which seems in conflict with the idea that aurally-presented verbal information has automatic access to a phonological store. Waters, Rochon, and Caplan (1992) argue that apraxic patients, who also present with verbal short-term memory deficits, suffer an impairment in forming articulatory plans, not in articulation or memory per se. They support this contention with evidence that these patients show patterns of verbal short-term memory effects similar to those of healthy individuals engaged in articulatory suppression, namely reduced or absent phonological similarity and word length effects with visual presentation. Consistently with the idea that memory itself is intact, when recognition rather than recall of auditory lists was tested in patients with reduced aural-verbal short-term memory spans, patients showed quite good performance even on 4-item lists, drastically better performance than with recall (Morey, 2015). In recognition, neither articulation nor articulatory planning would be required, but memory for the list is required. That patients perform quite well with recognition suggests that the deficit is not in memory per se, and that recall tests which require response planning and production in addition to memory underestimate these patients' memory capabilities. In both apraxia and the short-term memory deficit cases, it is possible that abilities to plan speech, rather than a short-term phonological store, were damaged. Thus, the patient cases that are cited as the theoretical back-bone of a phonological store even when experimental evidence would seem to disconfirm it need not be taken as definitive evidence for domain-specific short-term stores at all. Indeed, like the experimental evidence, the strongest existing patient evidence does not strictly conform to predictions and is capable of alternative interpretations. We therefore should not limit our interpretation of experimental hypothesis tests of working memory phenomena based on one interpretation of these patient data. Despite appeals to case evidence and to the flexibility with which information may be encoded into working memory, it remains possible that short-term memory phenomena might be explained within an account that does not posit short-term memory stores at all.

If the evidence afforded by supposed cases of auditory-verbal short-term memory deficits remains ambiguous, then the evidence afforded by possible cases of visual or spatial deficits is even more so. Patients said to have visual or spatial short-term memory deficits typically also present with declines in cognitive functioning more generally, making it difficult to definitively pinpoint their deficit to short-term memory. This absence of evidence is troubling for a multi-component working memory model featuring specialized short-term visual or spatial storage and rehearsal modules; surely if such modules existed, then a truly selective deficit would occasionally arise. However, this absence presents no problem for perceptual-gestural accounts of memory phenomena. An embodied framework invoking motor systems for rehearsal of memoranda quite naturally predicts superior memory for verbal stimuli that have recourse to articulatory-motor processes for re-activation than for visual or spatial memories, which have fewer obvious means of motor reactivation. Compared with well-practiced speech processes, it is difficult to imagine a plausible analogue for re-activating visual or spatial stimuli. Proposals for embodying visual memory include rehearsal-based manual motor sequences or eye movements. Evidence evaluating the effectiveness of gaze-based and manual “rehearsal” of spatial or visual material has been mixed. While manual suppression techniques, such as spatial tapping or engaging in repetitive motions can be shown to impair spatial memories (Guérard & Tremblay, 2008; Meiser & Klauer, 1999; Pecher, 2013), this seems to be the limit of any analogy between visuo-motor and articulatory suppression. Pecher demonstrated that the motions performed in a manual suppression task did not need to overlap with the motions afforded by visual objects in order to provoke interference. Smyth and Scholey (1992) searched for evidence that movement speed predicted spatial memory recall, akin to observed relationships between articulatory speed and verbal recall, but they found no evidence for this despite observing statistically significant but unexpected relationships between articulation speed and spatial memory.

Eye movements in particular can be shown to positively affect spatial memory recall, but again this relationship deviates from observed relationships between articulation and verbal recall in several telling respects. First, while it looks as though gaze sequences consistent with the spatial memory sequence result in superior performance (Tremblay, Saint-Aubin, & Jalbert, 2006) and glances toward irrelevant information systematically impair spatial recall (Guérard & Tremblay, 2011), path-consistent tracing is nonetheless inferior to no movement at all (Lange & Engebert, 2013). Stationary gaze does not produce worse recall than free gazing (Godijn & Theeuwes, 2012; Postle, et al., 2006), which is unexpected if you assume that gazes are explicitly used to strengthen spatial memory in the same way that repetitive speech is employed to maintain verbal lists. It has been suggested that it is not the eye movements themselves, but the preparation and planning to perform the movements that produces interference with spatial memory (Pearson, Ball, & Smith, 2014; Postle et al., 2006). While suppressing eye movements by making repetitive irrelevant saccades is more damaging for spatial sequential memory than for visual object memory (Postle, et al., 2006), it is not clear that this mechanism is specialized for deployment with visual-spatial sequences, because forced performance of sequence-consistent eye movements likewise harms verbal serial memory (Lange & Engebert, 2013). The broadest ideas about gaze assisting memory envision looking as a retrieval cue, but do not propose that this retrieval cue is only useful for prompting retrieval of visual memories. Ferreira, Apel, and Henderson (2008) surmise that looking at a place previously occupied by a stimulus can trigger memory for that stimulus. They do not propose this is a process specialized to aid in retrieving visual images; examples include looking back at the position of a speaker in order to better recall a recent utterance, or looking toward the position on a page where text was originally read. This differs drastically from articulatory rehearsal, which is believed to be useful for keeping specifically verbal information active.

Altogether, the available evidence about motor actions assisting memory suggests that verbal information has access to stronger systems for re-generating or activating sensory materials than visual or spatial materials do. This makes embodied accounts a parsimonious way to integrate domain-specificity into working memory models. They can naturally predict the resilience of verbal memories to interference from non-verbal materials without invoking custom short-term memory modules, and they likewise predict that visual and spatial materials would be more difficult to remember accurately because they cannot be readily re-produced by existing motor systems. However, embodied accounts are currently under-specified. Applied to memory, they have been successfully invoked to explain maintenance of serial verbal information, but attempts to explain visual memory via embodiment have mainly been restricted to showing that eye movements or motor affordances impact memory. There is consistent evidence of relationships between eye movements and other motor processes and memory, but these relationships are often small and the nature of systematic differences between the utility of these functions for different kinds of task are not yet clear. There is reason to think that perceptual and motor affordances for activating visual and verbal memories differ, and these contrasts should be systematically evaluated to generate novel predictions for memory phenomena.

Conclusions

One of the starkest gradients along which various models of working memory vary is in how short-term memory is explained. Models vary drastically, from proposing multiple specialized short-term memory buffers or rehearsal mechanisms (Baddeley, 2012; Barrouillet & Camos, 2015; Logie, 2011), to proposing a distinction between extremely active and somewhat less active memories (Cowan, 2005; Oberauer, 2013) or retrieval cues (Unsworth & Engle, 2007), to explicitly denying any need for short-term memory stores (Macken, Taylor, & Jones, 2015; Nairne, 2002). The apparent need to posit distinct short-term stores to explain neuropsychological case data and dual-task working memory research has so far stood in the way of mass adoption of more parsimonious models that propose fewer components. However, neither the neuropsychological evidence nor the dual-task literature provides strong support for a dedicated visual-spatial short-term memory system. Proposing distinct mechanisms for every stage of verbal and visual perception and memory may be unnecessary, and ought to be reconsidered. Though existing models vary in how well they capture the apparent difference in robustness of visual and verbal memories, no model perfectly manages to explain this. We should focus future efforts on testing and comparing more parsimonious ways to explain and predict domain-specific interference in working memory.

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Table 1. Effects of selective interference to the application of mnemonic strategies

Strategy Manipulation	Paper	Judge Brightness	Irrelevant Pictures	Static Visual Noise	Dynamic Visual Noise	Spatial Tracking	Movement / Spatial Tapping	Judge Matrix	Spatial memory	Verbal Memory	Irrelevant Speech
Spatial Brooks	Baddeley & Lieberman, 1980	-				+					
	Baddeley, et al., 1975					+					
	Beech, 1984	+					+				
	Logie, et al., 1990								+[+]	+	
	Postle, et al., 2006						-, +				
	Quinn 1988	+					+				
	Quinn & Ralston, 1986						+[1]				
Nonsense Brooks	Baddeley & Lieberman, 1980	+				-					
	Baddeley, et al., 1975					-					
	Beech, 1984	-					-				
	Logie, et al., 1990								+	+[+]	
	Postle, et al., 2006						+, -				
	Quinn 1988	+					+				
Peg-word	Baddeley & Lieberman, 1980					+					
	Logie, 1986		+		+			+[+]			-
	McConnell & Quinn, 2000				+						
	McConnell & Quinn, 2004				+						
	Quinn & McConnell, 1996		+		+						-
	Quinn & McConnell, 2006				+						

Rote Rehearsal	Baddeley & Lieberman, 1980			-		
	Logie, 1986	-	-		+	+
	McConnell & Quinn, 2000		-			
	McConnell & Quinn, 2004		-			
	Quinn & McConnell, 1996	+	-			+
	Quinn & McConnell, 2006		-			
Method of Loci	Baddeley & Lieberman, 1980			+		

Note. When reported, "+" indicates that a significant decrease in recall was observed, and "-" indicates that it wasn't. Sometimes, only the relevant interaction was reported. In those cases, the super-scripted + marks the condition that experienced the significantly greater decrement.

1. I included only the "incompatible" movement condition of Quinn & Ralston, 1988. This involved making a formulaic sequence of movements around a matrix, similarly to the spatial tapping tasks.

Table 2. Patients with apparent visual or spatial short-term memory deficits

Case type	**Paper**	**ID**	**Anatomy**	**Verbal STM?**	**Spatial STM?**	**Visual STM?**	**Visual or spatial LTM?**
Visual	Hanley, Pearson, & Young, 1990	E.L.D.	Right fronto-temporal	Normal	(See Hanley et al. 1991)	Mixed	Normal
	Ross, 1980	Case 2	Right medial occipital lobe	Normal	Normal	Mixed	Normal
	Wilson, Baddeley, & Young, 1999	L.E.	Unreported	Impaired	Normal	Impaired	Impaired (if verbal and motor strategies prevented)
Spatial	Bonni, et al., 2014	G.P.	Right dorso-mesial frontal lobe	Normal	Normal	Normal	Normal, selective impairment for spatial information with 10-20 sec delay
	Carlesimo, et al., 2001	M.V.	Right fronto-parietal	Normal	Impaired	Normal (but low)	Normal (but low)
	Hanley, Young, & Pearson, 1991	E.L.D.	Right fronto-temporal	Normal	Impaired	Impaired	Normal
	Lepore, et al. 2008	M.Z.	Unreported	Normal	Impaired	Mixed	Mixed
	Luzzatti, et al, 1998	E.P.	Anterior right temporal lobe	Normal (but details not reported)	Impaired	Not tested? Implied by intact retrieval of images in wrong spatial layout, but from long-term knowledge.	Impaired
	Ross, 1980	Case 1	Right hemisphere	Normal	Impaired	Mixed	Mixed

Note. Various measures of “short-term” memory reported in these papers varied considerably as to the delay period. For the purpose of constructing this summary, I considered short-term memory to be “mixed” when performance on some tests that the authors described as “short-term” memory was deficient compared to controls while other measures showed classed as “short-term” memory showed no deficit.

Table 3. Studies of visual short-term memory with dual-task manipulations coded for meta-analysis

Auditory Secondary Task				
Paper	Memoranda	Distractor Description	Decision Response Required	Included in Fig.:
Dell'acqua & Jolicoeur, 2000	Spatial patterns	Tone judgment	Yes	
		Listen to tones	No	
Fougnie, et al., 2015	Spatial patterns	Birdcall recognition	Yes	2a, 2b, 2c, 3
Fougnie & Marois, 2011	Color, shape, face arrays	Tone sequence recognition	Yes	2a, 2b, 3
Janczyk & Berryhill, 2014	Color arrays	Tone judgment	Yes	
Klauer & Stegmaier, 1997	Spatial sequences	Listen to tones	No	2a, 2b, 3
		Loudness judgement	Yes	2a, 2b, 3
		Tone judgment	Yes	2a, 2b, 3
Langerock, Vergauwe, & Barrouillet, 2014	Spatial sequences	Tone judgement	Yes	
Morey & Bieler, 2013	Color, shape, color-shape arrays	Tone judgement	Yes	2a, 2b, 2c, 3
Morey, et al., 2011	Color arrays	Tone sequence recognition	Yes	
Ricker, Cowan, & Morey, 2010	Shape arrays	Tone judgment	Yes	2a, 2b, 2c, 3
Saults & Cowan, 2007	Color arrays	Timbre-content recognition	Yes	
		Timbre-content-location recognition	Yes	
Smyth & Scholey, 1994	Spatial sequences	Listen to tone	No	2a, 2b, 3
Smyth, 1996	Spatial sequences	Listen to tone	No	2a, 2b, 2c, 3
Stevanovski & Jolicoeur, 2007	Color arrays	Tone judgment	Yes	2a, 2b, 2c, 3
		Listen to tone	No	2a, 2b, 2c, 3
Stevanovski & Jolicoeur, 2011	Color-orientation arrays	Tone judgment	Yes	2a, 2b, 2c, 3
Van Lamsweerde, Beck, & Elliott, 2015	Shape, color-shape arrays	Detect tone	No	2a, 2b, 2c, 3
Vergauwe, Langerock, & Barrouillet, 2014	Color-shape arrays	Tone judgment	Yes	
Zokaei, Heider, & Husain, 2014	Orientation arrays, motion direction	Timbre judgment	Yes	2a, 2b, 2c, 3
Verbal Secondary Task				
Paper	Memoranda	Distractor Description	Decision Response Required	Included in Fig.:
Allen, Baddeley, & Hitch, 2006	Color, shape, color-shape arrays	Arithmetic	Yes	2a
Allen, et al., 2012	Color, color-shape arrays	Arithmetic	Yes	
Allen, Baddeley, & Hitch, 2014	Color, shape, color-shape sequences	Arithmetic	Yes	

Barrouillet, De Paepe, & Langerock, 2012	Spatial sequences	Arithmetic	Yes	
Barton, et al., 1995	Spatial patterns	Articulatory suppression	No	2a, 2b, 3
Boduroglu & Shah, 2014	Spatial sequences	Articulatory suppression	No	
Brown & Brockmole, 2010	Color, shape, color-shape arrays	Arithmetic	Yes	
Cocchini, et al., 2002	Matrix patterns	Articulatory suppression	No	2a, 2b, 3
		Verbal memory	Yes	2a, 2b, 3
Cowan & Morey, 2007	Color arrays	Verbal sequence memory	Yes	2a, 2b, 2c, 3
Cowan, Saults, & Blume, 2014	Color arrays	Verbal sequence memory	Yes	2a, 2b, 3
Dent, 2010	Color arrays	Articulatory suppression	No	2a, 2b, 3
Depoorter & Vandierendonck, 2009	Spatial patterns, spatial sequences	Verbal item memory	Yes	2a, 2b, 3
		Verbal sequence memory	Yes	2a, 2b, 3
Duff, 2000	Spatial sequences	Verbal sequence memory	Yes	2a
Feng, Pratt, & Spence, 2012	Color arrays	Arithmetic	Yes	2a, 2b, 2c, 3
Fougnie, et al., 2015	Spatial patterns	Verbal item memory	Yes	2a, 2b, 2c, 3
Fougnie & Marois, 2011	Color, shape, face arrays	Verbal sequence memory	Yes	2a, 2b, 3
Fougnie & Marois, 2006	Color arrays	Verbal item memory	Yes	2a, 2b, 2c, 3
Karlsen, et al., 2010	Color, shape, color-shape arrays	Arithmetic	Yes	
Klauer & Stegmaier, 1997	Spatial sequences	Repeat words	No	2a, 2b, 3
Lilienthal, Hale, & Myerson, 2014	Spatial sequences	Arithmetic	Yes	2a, 2b, 3
Logie, Zucco, & Baddeley, 1990	Spatial patterns	Arithmetic	Yes	2a, 2b, 3
		Verbal sequence memory	Yes	2a, 2b, 3
Makovski, Shim, & Jiang, 2006	Natural scenes, color arrays, spatial arrays	Word judgment	Yes	2a, 2b, 2c, 3
		Listen to verbal input	No	2a, 2b, 2c, 3
Martein, Kemps, & Vandierendonck, 1999	Spatial sequences	Articulatory suppression	No	
Mate, Allen, & Baques, 2012	Color-shape arrays	Articulatory Suppression	No	2a, 2b, 3
Morey, et al., 2015	Color arrays	Arithmetic	Yes	
		Articulatory suppression	No	
Morey, et al., 2013	Color arrays	Verbal sequence memory	Yes	2a, 2b, 2c, 3
Morey & Cowan, 2004	Color arrays	Verbal sequence memory	Yes	2a
		Articulatory suppression	No	2a

Morey & Cowan, 2005	Color arrays	Verbal sequence memory	Yes	2a, 2b, 3
Morey & Mall, 2012	Spatial sequences	Listen to verbal input	No	2a, 2b, 2c, 3
		Verbal sequence memory	Yes	2a, 2b, 2c, 3
Morey & Miron, 2016	Spatial sequences	Verbal sequence memory	Yes	2a, 2b, 3
Nieuwenstein & Wyble, 2014	Kanji characters	Arithmetic	Yes	2a, 2b, 2c, 3
Pecher, 2013	Photos of objects	Articulatory suppression	No	2a, 2b, 2c, 3
Phillips & Christie, 1977a	Spatial patterns	Arithmetic	Yes	2a, 2b, 3
Phillips & Christie, 1977b	Spatial patterns	Arithmetic	Yes	2a, 2b, 2c, 3
		Listen to digits	No	2a, 2b, 2c, 3
		Read digits	No	2a, 2b, 2c, 3
Postle, D'Esposito, & Corkin, 2005	Spatial, shape arrays	Animacy judgment	Yes	2a, 2b, 2c, 3
		Part-of-speech judgment	Yes	2a, 2b, 2c, 3
Postle & Hamidi, 2007	Shape arrays	Listen to verbal input	No	2a, 2b, 2c, 3
Postle, et al., 2006	Spatial, shape arrays	Read words	No	2a, 2b, 2c, 3
Ricker & Cowan, 2010	Shape arrays	Arithmetic	Yes	2a, 2b, 2c, 3
		Repeat digits	No	2a, 2b, 2c, 3
Ricker, Cowan, & Morey, 2010	Shape arrays	Articulatory suppression	No	2a, 2b, 2c, 3
		Listen to verbal input	No	2a, 2b, 2c, 3
		Verbal recognition	Yes	2a, 2b, 2c, 3
Rudkin, Pearson, & Logie, 2007	Spatial patterns, spatial sequences	Random generation	Yes	2a
Shah & Miyake, 1999	Orientation arrays	Sentence verification	Yes	2a
Sims & Hegarty, 1997	Spatial patterns	Verbal reasoning	Yes	
Smyth & Pendleton, 1990	Movement sequences	Repeat word	No	2a, 2b, 3
Smyth & Scholey, 1992	Spatial sequences	Articulatory suppression	No	2a
Smyth & Scholey, 1994	Spatial sequences	Listen to verbal input	No	2a, 2b, 2c, 3
		Read	No	2a, 2b, 3
		Repeat word	No	2a, 2b, 3
Van Lamsweerde, Beck, & Elliott, 2015	Shape, color-shape arrays	Verbal recognition	Yes	2a, 2b, 2c, 3
Vandierendonck, 2016	Spatial pattern, spatial sequences	Verbal sequence memory	Yes	2a, 2b, 3
		Verbal item memory	Yes	2a, 2b, 3
Vandierendonck, et al., 2004	Spatial sequences, forwards	Articulatory	No	2a

	and backwards	suppression		
Vergauwe, Barrouillet, & Camos, 2010	Spatial sequences	Semantic categorization	Yes	
Vergauwe, et al., 2012	Spatial sequences	Semantic categorization	Yes	
Zokaei, Heider, & Husain, 2014	Orientation arrays, motion direction	Semantic judgment	Yes	2a, 2b, 2c, 3
Visual-Spatial Secondary Task				
Paper	Memoranda	Distractor Description	Decision Response Required	Included in Fig.:
Anderson, et al., 2008	Spatial patterns	Visual search	Yes	2a, 2b, 2c, 3
Andrade, et al., 2002	Spatial patterns, Chinese characters	Color memory	Yes	
		Dynamic visual noise	No	2a, 2b, 3
		Spatial tapping	No	2a, 2b, 3
Avons & Sestieri, 2005	Spatial patterns	Dynamic visual noise	No	2a, 2b, 2c, 3
		Static visual noise	No	2a, 2b, 2c, 3
Barton, et al., 1995	Spatial patterns	Spatial tapping	No	2a, 2b, 3
Boduroglu & Shah, 2014	Spatial sequences	Irrelevant color changes	No	2a
Cocchini, et al., 2002	Spatial patterns	Tracking	Yes	2a, 2b, 3
Cortese & Rossi-Arnaud, 2010	Spatial sequences	Spatial tapping	No	2a
Cowan & Morey, 2007	Color arrays	Color array memory	Yes	2a, 2b, 2c, 3
Della Sala, et al., 1999	Spatial patterns, location sequences	Spatial tapping	No	2a, 2b, 3
		View images	No	2a, 2b, 3
Dent, 2010	Color, spatial arrays	Dynamic visual noise	No	
Depoorter & Vandierendonck, 2009	Spatial patterns, spatial sequences	Spatial pattern memory	Yes	2a, 2b, 3
		Spatial sequence memory	Yes	2a, 2b, 3
Emrich, et al., 2010	Color arrays	Visual search	Yes	2a, 2b, 2c, 3
Ester, et al., 2014	Color arrays	Visual search	Yes	2a, 2b, 2c, 3
Fougnie & Marois, 2009a	Color-shape arrays	Tracking	Yes	2a, 2b, 2c, 3
Fougnie & Marois, 2009b	Color arrays	Color array memory	Yes	2a, 2b, 2c, 3
Fougnie & Marois, 2006	Color arrays	Tracking	Yes	2a, 2b, 2c, 3
		Color array memory	Yes	2a, 2b, 2c, 3
Johnson, Hollingworth, & Luck, 2008	Color-orientation arrays	Visual search	Yes	2a, 2b, 2c, 3
Klauer & Stegmaier, 1997	Spatial sequences	Localize visual image	Yes	2a, 2b, 3
		View image	No	2a, 2b, 3
Lawrence, Myerson, & Abrams, 2004	Spatial sequences	Spatial judgment	Yes	

Lilienthal, Hale, & Myerson, 2014	Spatial sequences	Spatial judgment	Yes	2a, 2b, 3
Logie, Zucco, & Baddeley, 1990	Spatial patterns	Image generation	Yes	2a, 2b, 3
Logie & Marchetti, 1991	Color arrays, spatial sequences	Spatial tapping	No	2a, 2b, 3
		View image	No	2a, 2b, 3
Makovski, Shim, & Jiang, 2006	Natural scenes, color arrays, spatial arrays	Picture judgment	Yes	2a, 2b, 2c, 3
		View image	No	2a, 2b, 2c, 3
Martein, Kemps, & Vandierendonck, 1999	Spatial sequences	Spatial tapping	No	
Matsukura & Vecera, 2009	Spatial, color, shape arrays	Visual judgment	Yes	2a, 2b, 2c, 3
		Visual search	Yes	2a, 2b, 2c, 3
Mishra, et al., 2013	Motion direction	Speed judgment	Yes	2a, 2b, 2c, 3
		View image	No	2a, 2b, 2c, 3
Myerson, et al., 1999	Spatial sequences	Color judgment	Yes	2a
		Localize visual image	Yes	2a
Oh & Kim, 2004	Spatial, color arrays	Visual search	Yes	2a, 2b, 3
Phillips & Christie, 1977b	Spatial patterns	View image	No	2a, 2b, 2c, 3
		Visual memory	Yes	2a, 2b, 2c, 3
Postle, D'Esposito, & Corkin, 2005	Spatial, shape arrays	Tracking	Yes	2a, 2b, 2c, 3
Rerko, Souza, & Oberauer, 2014	Color arrays	Color judgment	Yes	2a, 2b, 3
Ricker, Cowan, & Morey, 2010	Shape arrays	Spatial tapping	No	2a, 2b, 2c, 3
Sapkota, Pardhan, & van der Linde, 2013	Grayscale noise	Spatial tapping	No	2a, 2b, 3
Seemüller, Fieler, & Rösler, 2011	Motion direction	Orientation discrimination	Yes	2a, 2b, 2c, 3
Shah & Miyake, 1999	Orientation arrays	Mental rotation	Yes	2a
Shen, Huang, & Gao, 2015	Color, shape, color-shape, orientation, color-orientation arrays	Mental rotation	Yes	2a, 2b, 2c, 3
		Motion discrimination	Yes	2a, 2b, 2c, 3
		Visual memory	Yes	2a, 2b, 2c, 3
		Visual search	Yes	2a, 2b, 2c, 3
Sims & Hegarty, 1997	Spatial patterns	Spatial reasoning	Yes	2a, 2b, 2c, 3
Smyth & Pendleton, 1990	Movement sequences	Location memory	Yes	2a, 2b, 3
		Movement memory	Yes	2a, 2b, 3
		Spatial tapping	Yes	2a, 2b, 3
		View image	No	2a, 2b, 3
Smyth & Scholey, 1994	Spatial sequences	Spatial judgment	Yes	2a, 2b, 3
		View image	No	2a, 2b, 2c, 3

Vandierendonck, et al., 2004	Spatial sequences, forwards and backwards	Spatial tapping	No	2a
Vergauwe, Barrouillet, & Camos, 2010	Spatial sequences	Spatial judgment	Yes	
Vergauwe, Barrouillet, & Camos, 2009	Spatial patterns, spatial sequences, Chinese characters	Color judgment	Yes	2a, 2b, 2c, 3
		Motion judgment	Yes	2a, 2b, 2c, 3
		Spatial judgment	Yes	2a
		Symmetry judgment	Yes	2a
Wood, 2007	Movement sequences, color arrays, spatial arrays, color sequences	Color array memory	Yes	2a, 2b, 2c, 3
		Color sequence memory	Yes	2a, 2b, 2c, 3
		Movement sequence memory	Yes	2a
		Spatial array memory	Yes	2a, 2b, 2c, 3
Wood, 2011a	Color sequences, movement sequences, shape arrays, color arrays	Color array memory	Yes	2a, 2b
		Color sequence memory	Yes	2a, 2b, 2c, 3
		Movement sequence memory	Yes	2a, 2b, 2c, 3
		Shape array memory	Yes	2a, 2b
Wood, 2011b	Color arrays, spatial arrays, shape arrays, Color-shape arrays	Color array memory	Yes	2a, 2b, 2c, 3
		Color-shape array memory	Yes	2a, 2b, 2c, 3
		Shape array memory	Yes	2a, 2b, 2c, 3
		Spatial array memory	Yes	2a, 2b, 2c, 3
		Visual search	Yes	2a, 2b
Woodman, Vogel, & Luck, 2001	Color, orientation arrays	Visual search	Yes	2a, 2b, 3
Woodman & Luck, 2004	Spatial arrays	Visual search	Yes	2a, 2b, 2c, 3
Woodman, Luck, & Schall, 2007	Color arrays	Visual search	Yes	2a, 2b, 3
Zhang, et al., 2010	Color, color-shape arrays	Tracking	Yes	2a, 2b, 2c, 3
Zimmer, Speiser, & Seidler, 2003	Object arrays, spatial sequences	Dynamic visual noise	No	2a, 2b, 3
		Spatial tapping	No	2a, 2b, 3
		View image	No	
Zokaei, Heider, & Husain, 2014	Orientation arrays, motion direction	Visual search	Yes	2a, 2b, 2c, 3
Other Secondary Task				
Paper	Memoranda	Distractor Description	Decision Response Required	Included in Fig.:
Cortese & Rossi-Arnaud, 2010	Spatial sequences	Manual suppression	No	

Martein, Kemps, & Vandierendonck, 1999	Spatial sequences	Random interval generation	No	
Pecher, 2013	Photos of objects	Manual suppression	No	
Postle & Hamidi, 2007	Shape arrays	Saccade suppression	No	
Postle, et al., 2006	Spatial, shape arrays	Saccade suppression	No	
Rudkin, Pearson, & Logie, 2007	Spatial patterns, spatial sequences	Fixed interval generation	No	
		Random interval generation	Yes	
Seemüller, Fiehler, & Rösler, 2011	Motion direction	Kinesthetic discrimination	Yes	
Smyth & Pendleton, 1990	Movement sequences	Manual suppression	No	
Vandierendonck, et al., 2004	Spatial sequences, forwards and backwards	Random interval generation	Yes	

Figure 1

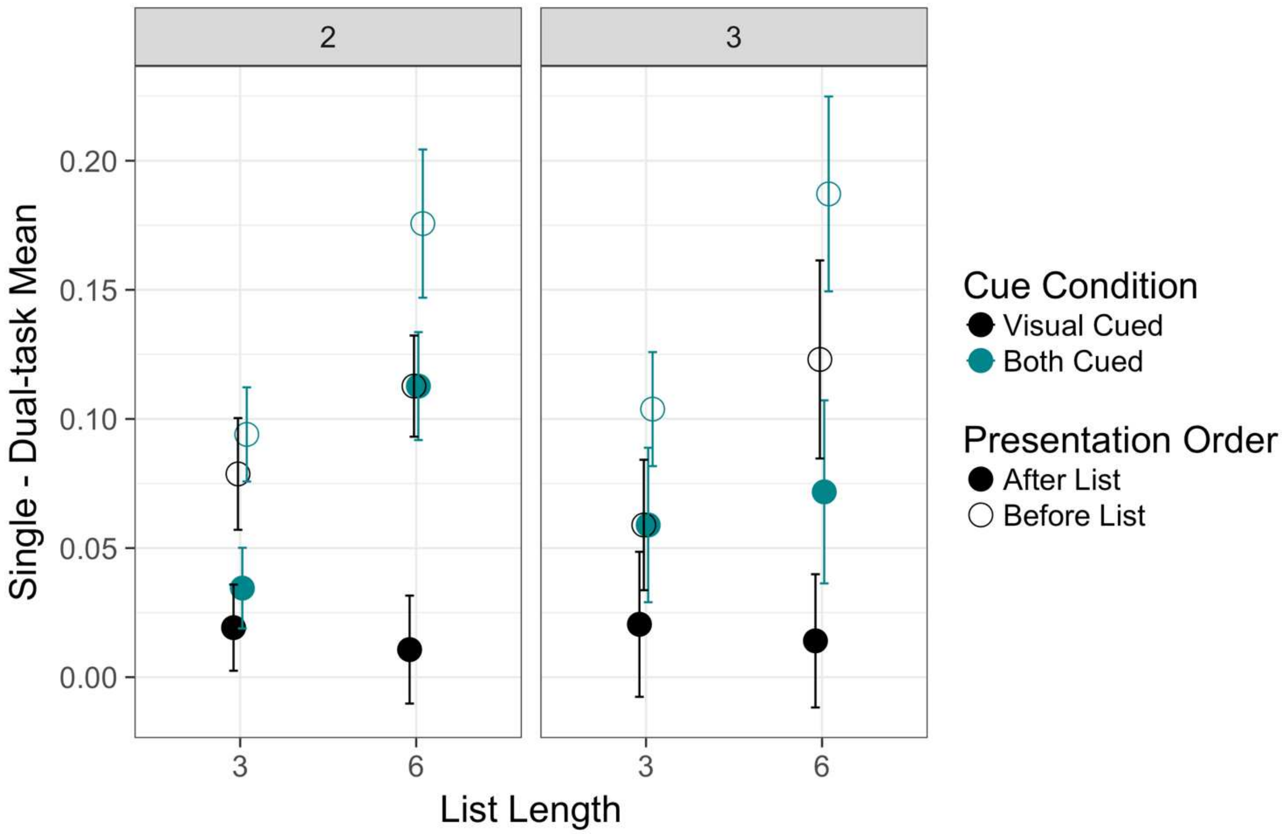

Figure 1. Dual-task costs for arrays of two (left) or three (right) visual items in Experiments 1a, 1b, 2a, and 2b of Morey, et al., 2013. Left panel *N*=49, right panel *N*=26. Black parameters are for trials in which the visual array was retro-cued for testing. Teal parameters indicate that no informative retro-cue was given. Open shapes depict trials in which visual arrays were presented before verbal lists, and in filled shapes visual arrays were presented after the verbal lists. Error bars are standard errors of the mean with the Morey-Cosineau (Morey, 2008) correction applied.

Figure 2

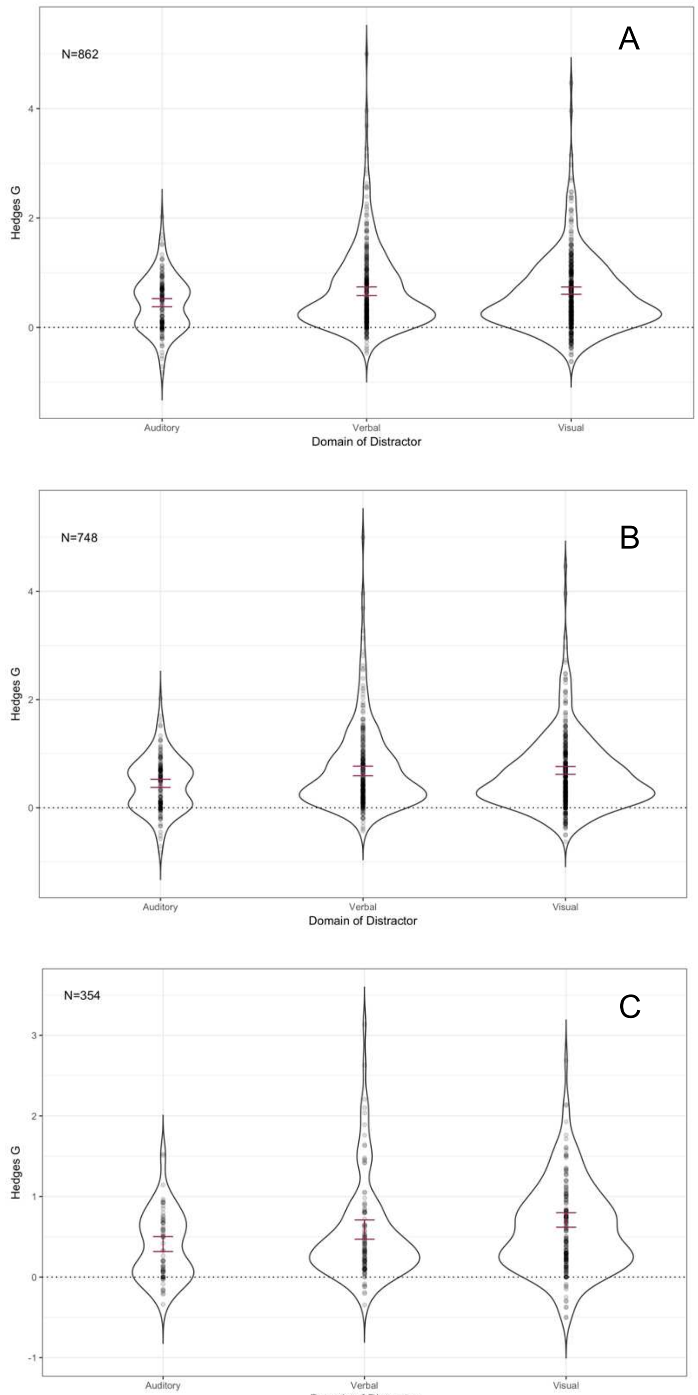

Figure 2. Violin plots depicting the distributions of Hedges G effect size values calculated on the difference between single-task and dual-task performance on visual memory tasks, organized by the domain of the secondary task. 2a includes all 862 observations meeting all criteria. 2b is restricted to observations with retention intervals of at least 1000 ms. 2c is additionally restricted to observations where the visual memory task set size was no more than 3. Regions marked in purple are the 95% credible intervals surrounding the mean effect size, weighted by the sample size of each point.

Figure 3

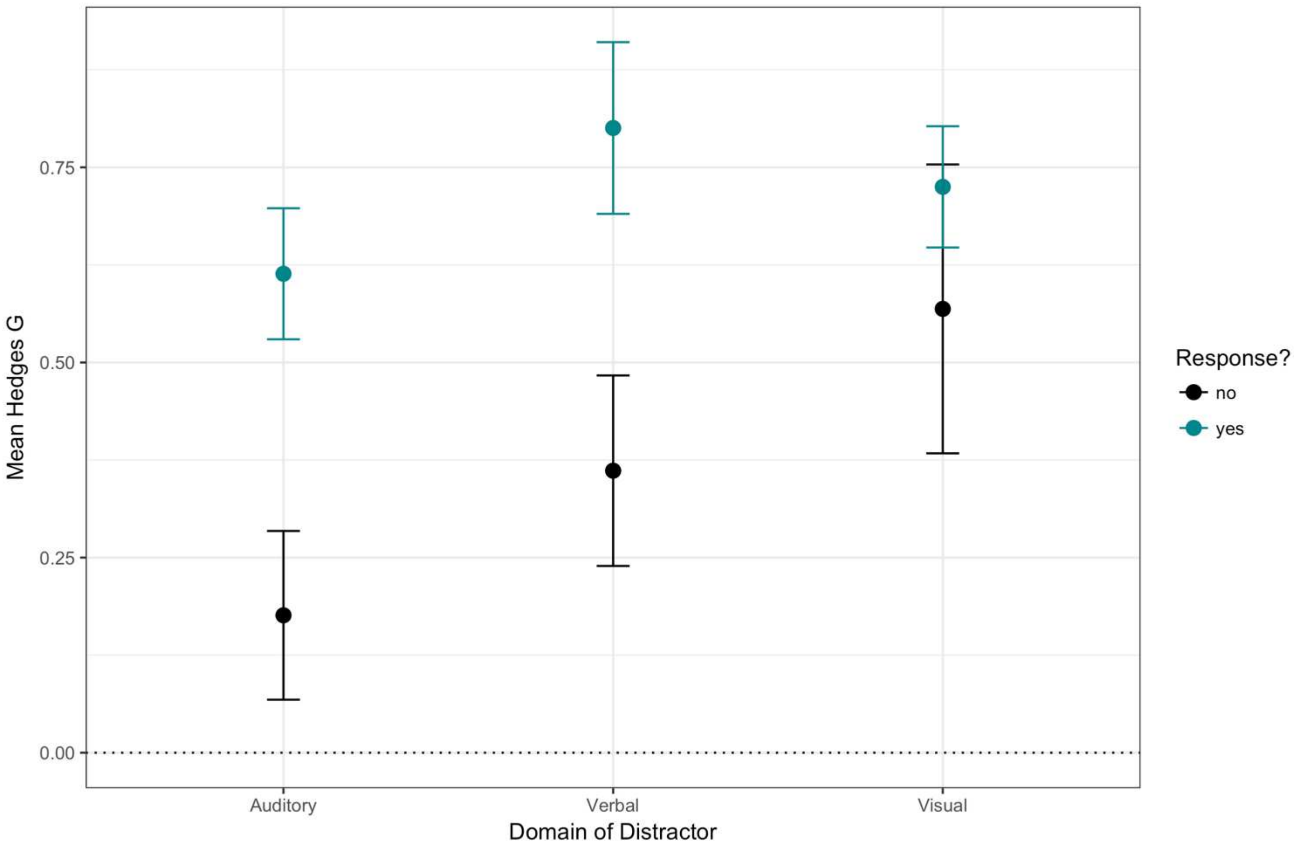

Figure 3. Mean Hedges G, weighted by the sample size, for comparisons involving auditory, verbal, or visual secondary tasks that varied by whether they required a non-repetitive decision or response. Error bars are 95% credible intervals. *N*=748.